ELECTRICITY IN THE SERVICE OF MAN

ELECTRICITY
IN THE
SERVICE OF MAN

A POPULAR AND PRACTICAL TREATISE ON THE APPLICATIONS OF ELECTRICITY TO MODERN LIFE

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WITH OVER 3,000 ILLUSTRATIONS

VOLUME II

TECHNOLOGY OF ELECTRICITY
Section II

CASSELL AND COMPANY, LTD
London, New York, Toronto and Melbourne
1919

MAY 4 - 1922

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ELECTRICITY

IN THE SERVICE OF MAN

PART II

The Technology of Electricity

CHAPTER V

ALTERNATE-CURRENT MOTORS

THE elementary principles underlying the working and construction of alternate-current motors, both monophase and polyphase, having been dealt with in detail in Vol. I. (*see* pages 606 to 627), the present chapter will be devoted chiefly to showing how those principles are applied in modern motors, and for this purpose several representative machines will be described, and attention will be called to further consequences of the leading principles involved either in working or construction. The polyphase motor for a long time received the greater share of attention, and was the more widely used; it therefore seems desirable to deal with it first, more especially since it illustrates in a form readily followed, as will be gathered from what has been written in the previous volume, the starting devices found necessary with many types of monophase motors.

As explained already in Vol. I., even polyphase motors fall into several distinct types, which may be summarised as follows :—

- (*a*) Synchronous motors.
- (*b*) Induction motors.
- (*c*) Commutator motors.
    - (i.) Series or shunt.
    - (ii.) Repulsion.

Of these (*a*), the synchronous motor, is simply a reversed generator, and runs at one definite speed, which is fixed by the number of its poles and the frequency of the supply current. Its motor use is limited by this restriction of its speed to such applications as transmission drives, coupled plant, etc., but it has another use, with which we deal later, as a device for improving the power factor of the circuit. Many forms of generators which can be used as synchronous motors have already been described, and therefore we pass on to the more widely used types, though it is now recognised that for motor use a synchronous machine should be as specially designed as it is for generator use. The difficulty of the *starting of the synchronous motor* is referred to later (*see* page 715).

I. POLYPHASE INDUCTION MOTORS

It may be recalled that polyphase induction motors consist electromagnetically of two parts: (i.) the **stator,** into which the line or working current is introduced, and which, as its name implies, is fixed; and (ii.) the **rotor,** which revolves and in which only induced currents flow, there being no conducting connection with the line circuit. This constitutes the chief advantage of the induction motor, for, in addition to the absence of a commutator, the great drawback of a continuous-current motor, it has no rubbing contacts, and therefore no mechanical friction other than that which is inseparable from any piece of rotating machinery, namely, windage and the friction of the bearings. It is true that in the larger sizes—say, from 5 B.H.P. upwards—it is often found desirable or even necessary to provide the rotor windings with slip rings, which somewhat detract from the simplicity of the machine; but these are only used for starting purposes, and, when full speed has been attained, are usually short-circuited so that the brushes may be lifted.

It may further be recalled that the polyphase current in the stator windings provides a rotating field the angular velocity of which depends upon the number of revolving poles, or pairs of poles, and the frequency or periodicity of the line current. This angular velocity can easily be calculated as the number (n_1) of complete revolutions per minute, and is (*see* page 621, Vol. I.)

$$n_1 = \frac{60\,n}{p} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where n is the periodicity of the current supplied in periods per second, and p is the number of *pairs* of poles formed by the stator. Under ordinary working conditions the motor is not quite, but is *nearly, synchronous*—that is, the speed, in R.P.M., is nearly constant and equal to n_1. The actual speed is less than n_1 by a small percentage, known as the *slip* (*see* page 613, Vol. I.). The amount of slip (s) expressed as a percentage of n_1 is connected with the actual speed (R.P.M.) by the equation

$$\text{R.P.M.} = \frac{60\,n}{p}\left(1 - \frac{s}{100}\right) \quad . \quad . \quad . \quad . \quad (2)$$

from which the slip can be calculated when the other quantities are known.

Without some slip the rotor cannot take power from the stator, and the machine therefore cannot work as a motor. For if $s = 0$ we have

R.P.M. $= n_1$, and the conductors of the rotor would therefore be revolving as rapidly as the rotating field. They would in this case be keeping step with the moving lines of force and would not be cutting them; therefore no E.M.F.S would be induced in these conductors, consequently no currents would flow, and in the absence of currents in the rotor there would be no mechanical action between the rotor and the stator, and no energy could be transferred from one to the other. To maintain such a speed and to supply energy for the frictional losses the rotor would have to be mechanically driven, and it is easy to show that if with such a mechanical drive the rotor be speeded up *above* the synchronous speed, n_1, energy will flow in the reverse direction from the rotor to the stator, and the machine will then act as a *generator* supplying power to the line circuit. Attempts have been made from time to time to utilise this property of induction motors, and it has been utilised for regulating purposes, for regenerative working in electric traction problems, and in other directions.

The essential parts of typical polyphase induction motors have been illustrated in Vol. I. (pages 618-623). In selecting for further illustration modern examples of such motors, the difficulty experienced in other parts of this book is again encountered—that is to say, that their manufacture is now so widely undertaken by first-class firms that the material available is many times in excess of that for which space can be found. The description of the machines of certain firms must not therefore be taken to imply that those of other firms are necessarily inferior.

The chief classes of polyphase induction motors are the "squirrel-cage" motor and the "slip-ring" or wound motor, the distinctive name being derived from the type of rotor used (*see* Vol. I., pages 618 and 620). The first-named class has the great advantage of simplicity, since it has no rubbing contacts and is quite self-contained. It has, however, the disadvantage that its starting torque is inferior to that of a slip-ring motor, and that it cannot start against a considerable load without heavy and phase-disturbing starting currents. For small motors it may be said that the squirrel-cage motor is most widely used, whilst for very heavy work the slip-ring motor holds the field. In the intervening region the selection of a suitable motor depends on the conditions under which it is required to work, and therefore, as regards output, there is a wide region in which the two classes overlap and compete in their adaptability to service conditions.

In Figs. 692 to 699 and on Plate XII. particulars are given of the standard polyphase induction motors manufactured by Messrs. Bruce Peebles and Co., of Edinburgh. The particular size selected for description is known by the catalogue number as D 15; its output under various conditions of windings and working is referred to later (*see* page 692). It is made in various types similar to those already described in connection with continuous-current motors (*see* page 616, Section I.), such as "protected," "semi-enclosed," "totally enclosed," "pipe ventilated," "mining," etc., and with either a "squirrel-cage" or a "wound" rotor, the latter being, of course, supplied with slip rings.

An external view of the "protected" type with squirrel-cage rotor is shown in Fig. 692. The machine stands 35⅜ inches high, is 44⅞ inches wide, and 44 inches long to the end of the shaft carrying the pulley. The slip rings, which have to be added to the machine when supplied with a wound rotor, increase the length by 12½ inches. The chief external features of the motor can be made out from the figure, and do not call for any special description.

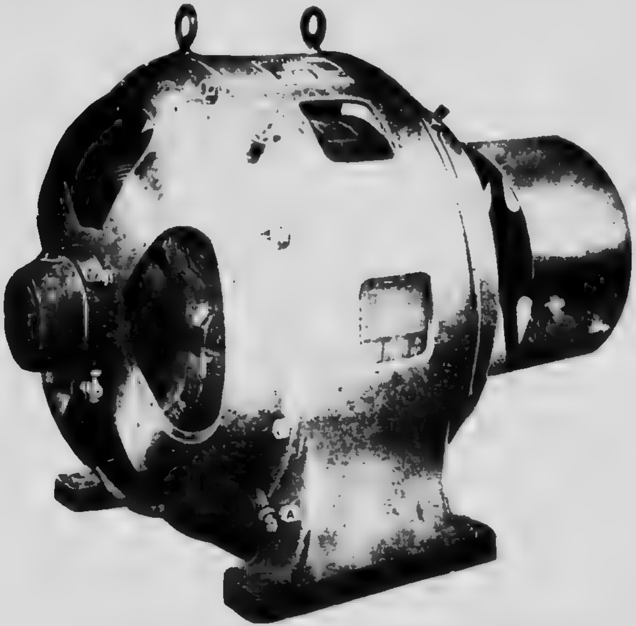
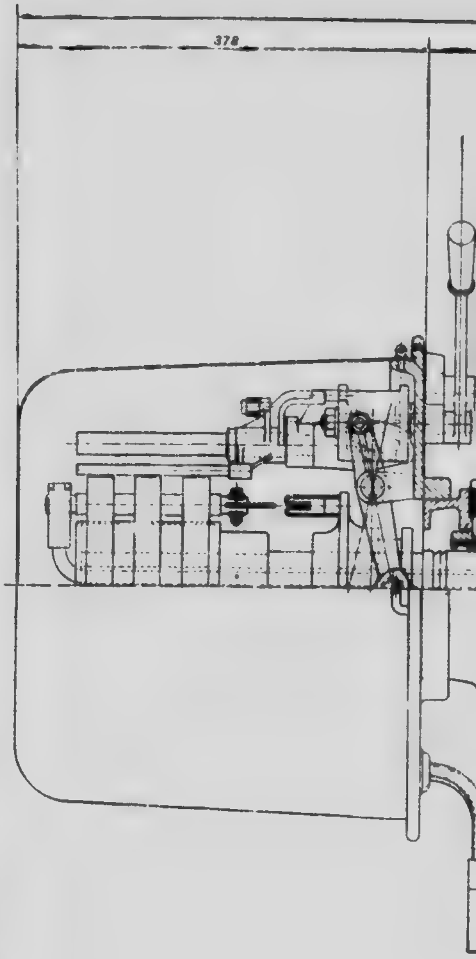
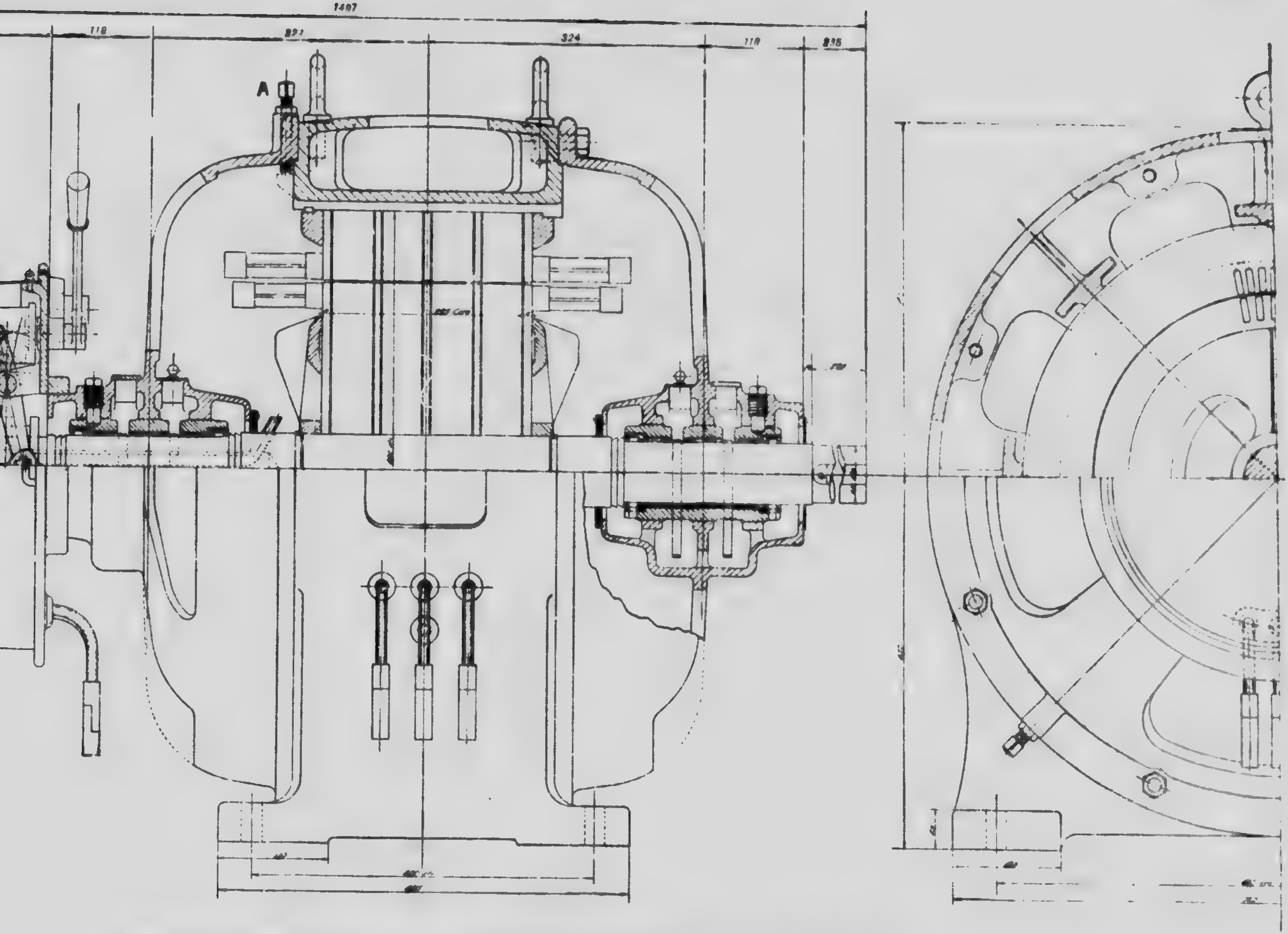


Fig. 692.—Peebles Standard Protected-type Squirrel-cage Polyphase Motor.

The chief details of a motor of this size are given in Plate XII. In this case the machine selected has a wound rotor, and particulars are given of the slip rings. The drawing has also the principal dimensions marked on it, these dimensions, however, being in millim[illegible] and not in inches. The cores of both stator and rotor are built up t[illegible] length of 225 mms. (8·9 inches), including three ventilating ducts in each case, and are clamped by end plates 10 mms. (0·4 inch) thick. The outer diameter of the stator core is 600 mms. (23·6 inches), and its inner diameter 435 mms. (17·1 inches). The outer diameter of the rotor core is 433·3 mms., thus giving an air gap only 0·85 mm. (0·033 inch) wide, just sufficient for mechanical clearance. This air-gap can be very accurately adjusted by means of four set-screws in each of the end covers. One of these is shown at A in Fig. 692 and in the plate. The slots in both stator and rotor are very nearly closed, there being 96 slots in the stator and 72 in the rotor, these numbers not being identical, for reasons

PLATE XII.





Messrs. Bruce Peebles and Co.'s 14-B h.p. Three-phase Induction Motor with Wound Rotor.

given at page 714. One of the stampings used for the stator core is shown in Fig. 603, and one of the rotor stampings in Fig. 604. Except where otherwise marked, all dimensions are given in millimetres. It will be noticed that the rotor stampings are keyed directly to the shaft, but are provided with ample ventilating ducts. The stator stampings are similarly keyed to the housing. In both cases the slots are 30 mm. deep by 8 mm. wide, with openings 2 mm. wide towards the air gap. The iron used is No. 27 S.W.G., and is therefore 0·016 inch thick. The successive stampings are insulated from one another in one of the usual ways.

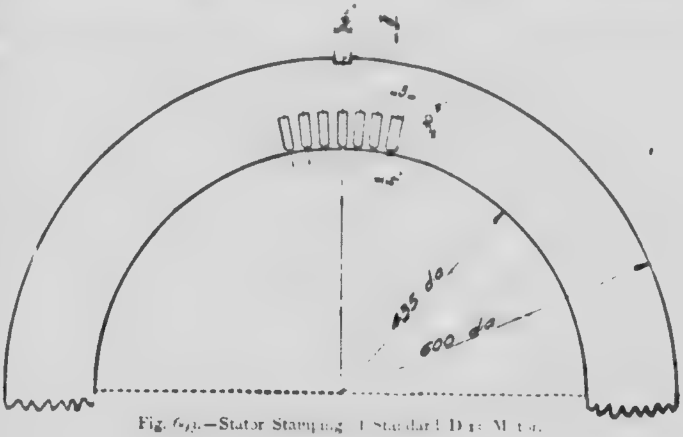


Fig. 603.—Stator Stamping of Standard D 15 Motor.

These stampings are assembled in an iron casting shown in Plate XII., the interior of the casting being accurately bored to receive them. They are carefully insulated, and the clamping end plates are secured by keys to avoid the use of through bolts, in which wasteful eddy currents may be set up. The appearance of a completed

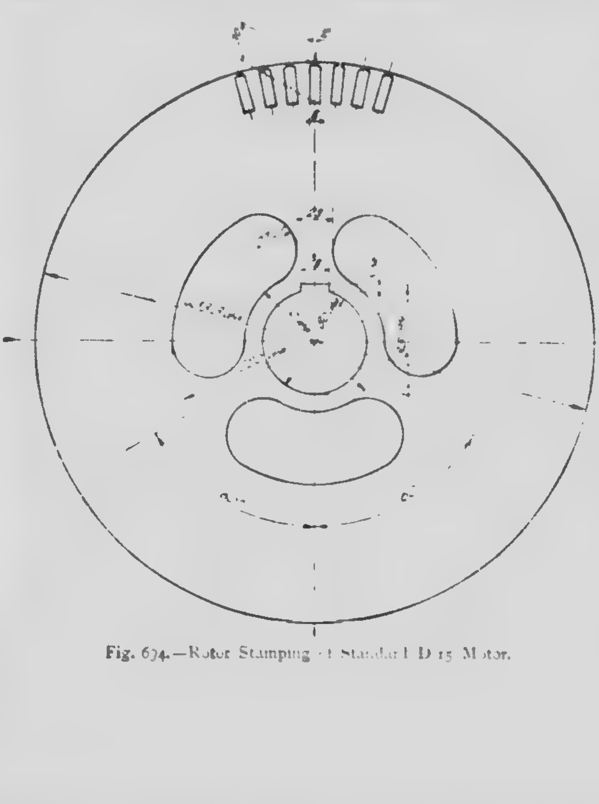


Fig. 604.—Rotor Stamping of Standard D 15 Motor.

stator carcass is shown in Fig. 695, which shows the unwound stator of a similar but somewhat smaller machine (size D 12) built by the same firm. The appearance of a stator after it is wound can be inferred from Fig. 696, which is also reproduced from a workshop photograph of a still smaller (size D 9) machine. The winding shown is for a four-pole machine with four slots per pole per phase. It is intended for a 550-volt 25-cycle circuit, and the machine is rated to give 12·5 B.H.P. at 722 R.P.M. It will be noticed that for this size there is only one ventilating duct in the stator core.

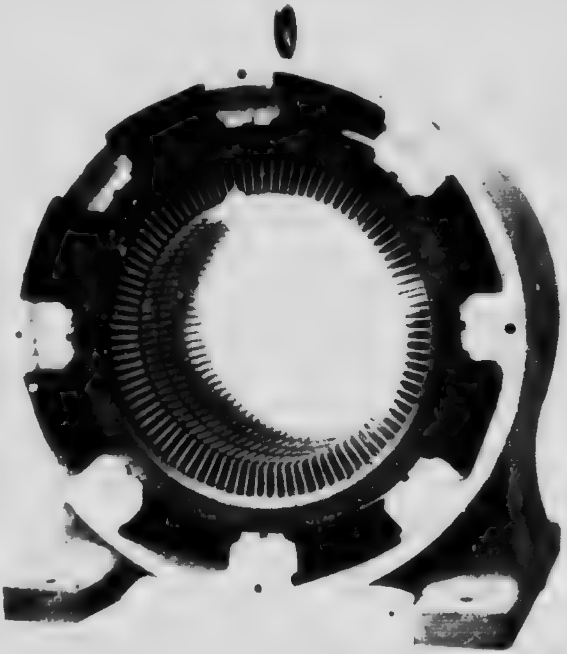


Fig. 695.—Unwound Stator of Standard D 12 Motor.

The rotor stampings are shown in Plate XII., as assembled directly on the shaft; for the larger sizes of the series a cast-iron spider of rigid design is used. In all cases, as in the stator, the use of through bolts is avoided, the end clamping plates being secured by keys. One of these rotors fully wound and of the squirrel-cage type is shown in Fig. 697. It is for a large machine, and has its core carried by a spider. The winding consists of a series of bare copper bars driven into the slots. They are connected together at both ends by rings of a special alloy, cast solid on to the ends of the copper bars, making a joint with each bar which is both mechanically and electrically perfect, and which avoids the possibility of trouble due to defective jointing.

A completed wound rotor with its slip rings is shown in Fig. 698, the particular rotor selected being the D 15 size, represented in Plate XII., one of the stampings of which, showing the principal dimensions, has already been given in Fig. 694. It will be noticed that three ventilating ducts are provided, as shown in the plate, and that, whilst there are no binding wires recessed in the armature iron, the end connectors are very strongly bound down to keep them in their places. The actual winding on the

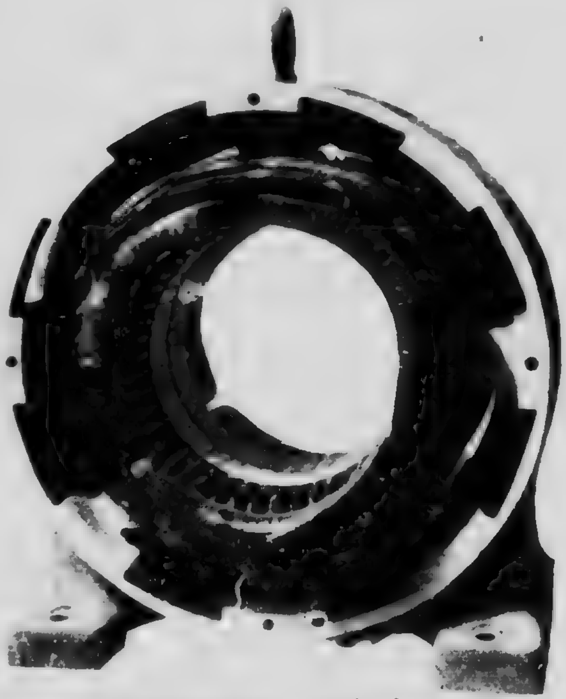


Fig. 676.—Wound Stator of a Standard [illegible] Motor.

armature shown is for 220 volts three-phase at 60 cycles, the rotor being intended to run at 680 R.P.M., and to give a full-load output of 14 B.H.P. The three leads from the windings to the slip rings can be clearly seen emerging from the hollow shaft.

The slip rings, which are shown in the drawing in Plate XII., are ¾ inch wide and designed to carry 200 amperes per phase; they are provided with the special short-circuiting arrangement used by this firm, which is separately described later (*see* page 735). The connections from the rotor windings to the slip rings are carried along the hollow shaft, and the slip rings and gear are protected by a cap which completely encloses them, but can be readily removed when necessary. The three-phase terminals of the stator winding are brought out in the shape of flexible cables at the side of the machine, whilst the flexibles for connecting the slip-ring brushes to the starting resistances are brought out at the back of the

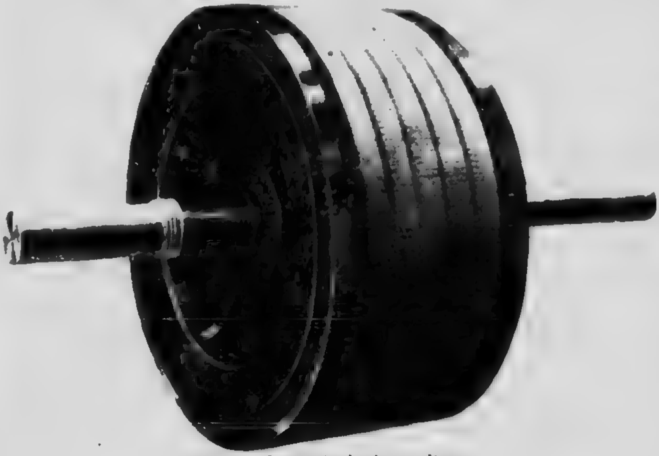


Fig. 677.—Large Squirrel-cage Rotor.

plate to which the protecting cover is attached. The shaft at the pulley or power end is solid and 65 mms. (2·56 inches) in diameter. It is carried by substantial bearings made of cast-iron lined with white metal, and is lubricated by loose rotating rings, the journal box being about 236 mms. (9·3 inches) long. The other mechanical details of the motor are thoroughly well designed throughout.

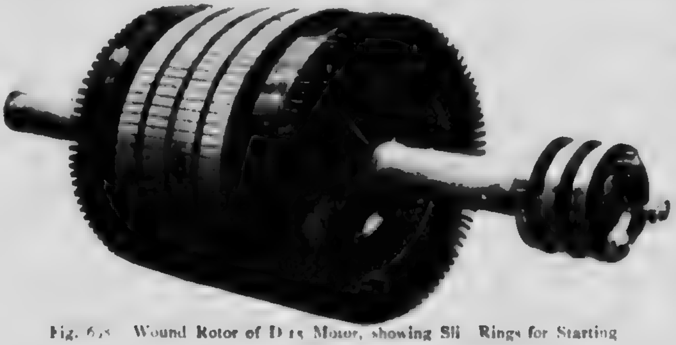


Fig. 698. Wound Rotor of D 15 Motor, showing Slip Rings for Starting

This description of a particular line of polyphase induction motors can well be concluded with an illustration (Fig. 699) of one of the larger sizes (D 30). The machine shown is designed to give 200 B.H.P. on a 500-volt 50-cycle circuit at 485 R.P.M. The bedplate of this machine is 70 inches long and 62 inches wide, the machine standing 52½ inches high. It will be instructive to compare such details as can be ascertained by inspection with the corresponding details of the smaller machines. The performance curves of a slightly larger machine, designed for 300 B.H.P. at 500 volts and 50 ∿, are given in Fig. 700. It will be noticed that the efficiency at full load is 94 per cent., and that efficiencies of over 90 per cent. are maintained from one-quarter load to a 50 per cent. overload. Also the power factor at full load is as high as 0·9 and the slip only about 2 per cent. Further notes on performance will be found on page 761.

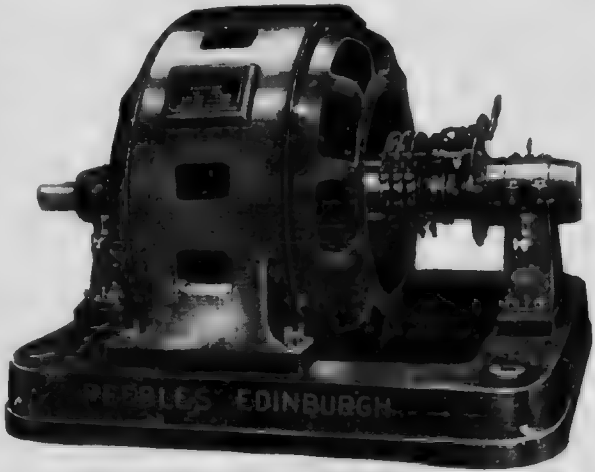


Fig. 699. A 200-B.H.P. 500-Volt Slip-ring Polyphase Motor.

With these examples to refer to, we may now proceed to consider some of the details of design and construction as generally adopted in polyphase induction motors.

The Magnetic Circuit.—Since the magnetic fluxes in both the stator and the rotor of an induction motor are continually changing in position, both in space and also in regard to the iron through which they pass, the magnetic circuit or circuits are not so definite as they are in continuous-current motors or in continuous- or alternate-current generators. Both the stator and rotor in their construction resemble the armatures of c.c. machines more nearly than the field-magnets, and the fluxes and resulting poles at any instant depend upon the currents flowing in the conductors on both sides of the air-gap and their phase relations at that instant. The iron cores therefore take the form of armature cores, fixed or rotatory, according as they belong to the stator or the rotor. They are invariably laminated and either slotted or tunnelled, a smooth core winding being unknown, so that the only room for variation lies in the shape of the slots, the width of the air gap, and the details of the yokes. The whole circuit provided for the flux in any given position is very compact, and the greatest part of the magnetic reluctance is in the air-gap, the thickness (or, rather, the thinness) of the teeth being next in importance.

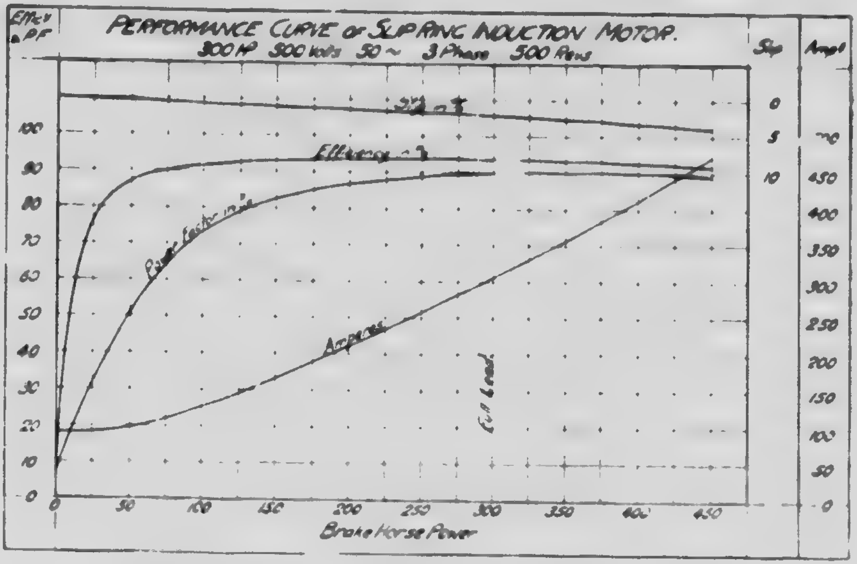


FIG. 700.—Test Curves of a Standard 300-B.H.P. Three-phase Induction Motor.

The Stator.—In regard to stators two different forms of slots are in common use—namely, the straight-sided open slot, which in the early days was perhaps more generally adopted by English and American designers

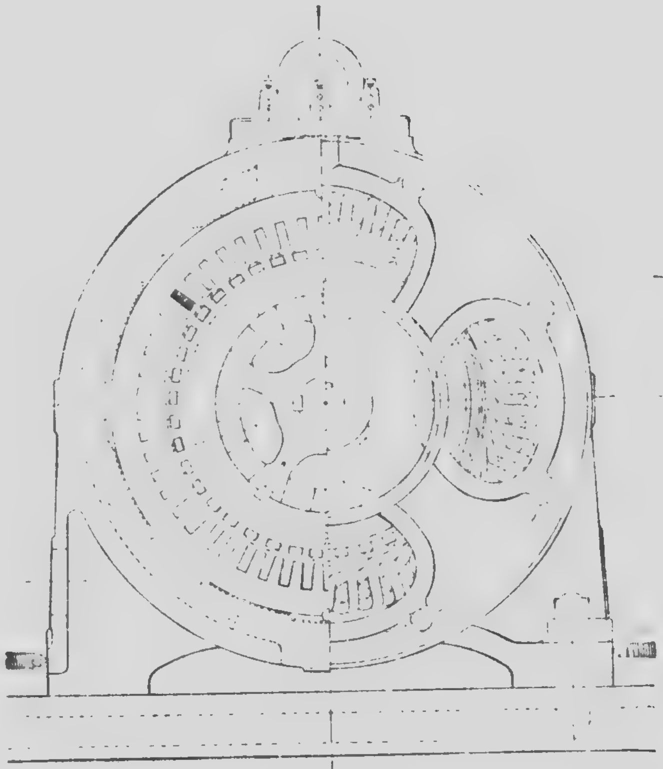


Fig. 701.

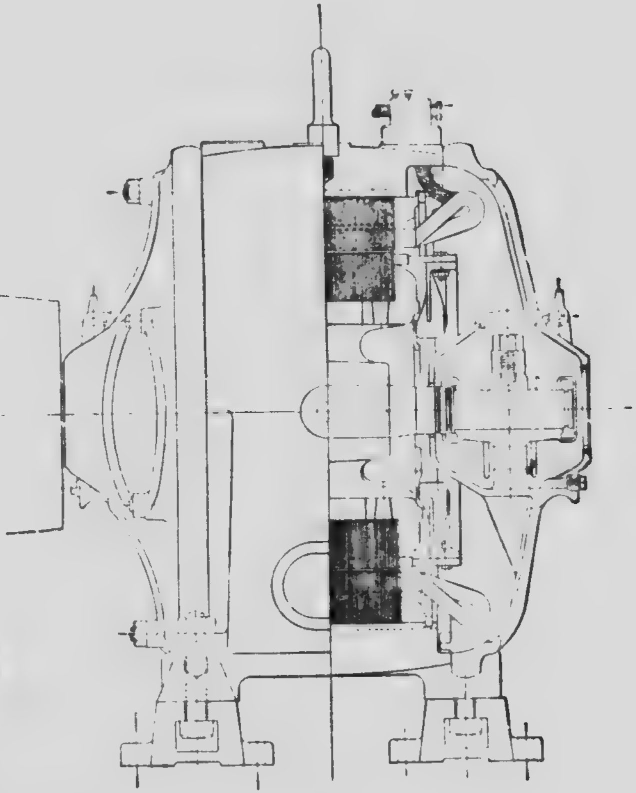


Fig. 702.

5 B.H.P. Induction Motor.

and the nearly or completely closed slot or tunnel, which was more characteristic of Continental practice.

An example is given in Fig. 701, which is an end view partly in section of a 5 B.H.P. induction motor with the slots and teeth of the stator having straight sides. Further details of the magnetic circuit of this machine, especially in regard to the depth of the laminated cores of both stator and rotor, are given in Fig. 702, which is a side view, also half in section. The stator is 12 inches in internal diameter, and has 54 slots, each 0·344 inch wide and 1 inch deep. The teeth are almost exactly of the same width as the slots. The air-gap between stator and rotor is only 31·25 mils, or $\frac{1}{32}$ inch wide, and attention may be called to the general design and the method by which the bearings are supported by the end brackets.

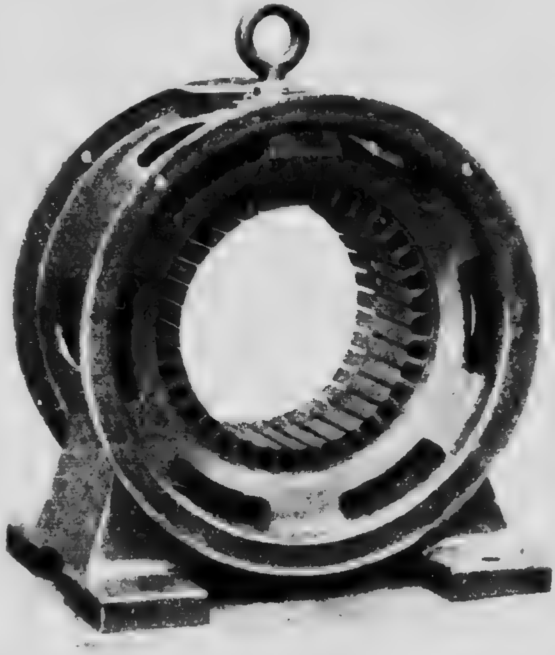


Fig. 703.—Unwound Stator of an Induction Motor with Slots nearly [illegible]

Turning now to the other type of stator core, with nearly closed slots, Fig. 703 represents the housing and the unwound core of an induction motor in which the space allowed for the windings is relatively much greater than that occupied by the dividing teeth, but the latter are expanded at their outer ends so as to close up almost completely the slot, which is approximately square. The other parts of the core, though differing in details, are magnetically the same as in the preceding cases.

Another example of a modern induction motor in which the slots of the stator are nearly closed is given in Figs. 704 and 705, which represent a longitudinal cross-section (Fig. 704) and an end view partly in section (Fig. 705) of a standard type of induction motor built by the Brush Electrical Engineering Company. The shape of the slots in both the stator and the rotor will be seen at *a a* in Fig. 705, and the details of the assembling and fixing of the stator stampings, as well as their shape, will be readily made out. One central ventilating duct is shown in both stator and rotor. The machines are made in fourteen sizes, with outputs ranging from 3 to 200 B.H.P., according to the speed and to the periodicity of the supply current. The extreme dimensions in inches of some of the principal parts of these sizes are shown on the drawings, and the wound stator of one of the largest size is shown in Fig. 706. This stator is bar-wound for heavy loads at comparatively low voltages.

A stator in which the windings are nearly enclosed by the iron has already been illustrated in the Bruce Peebles machine (Fig. 696), and we gave, in Figs. 693 and 694, dimensioned details of its stampings. In Figs. 707 and 708 we now give details of the stator stampings of a machine which was very fully described in the last edition, and which is representative of the type in which the windings are completely enclosed by the iron, that is, in which the slots become tunnels. Fig. 707 shows the

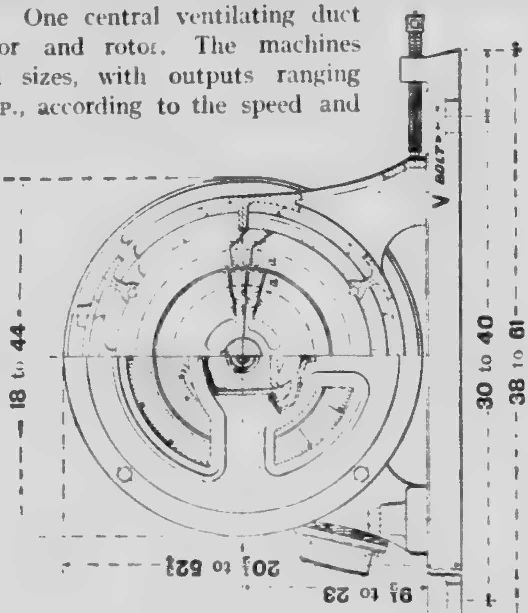


Fig. 705.

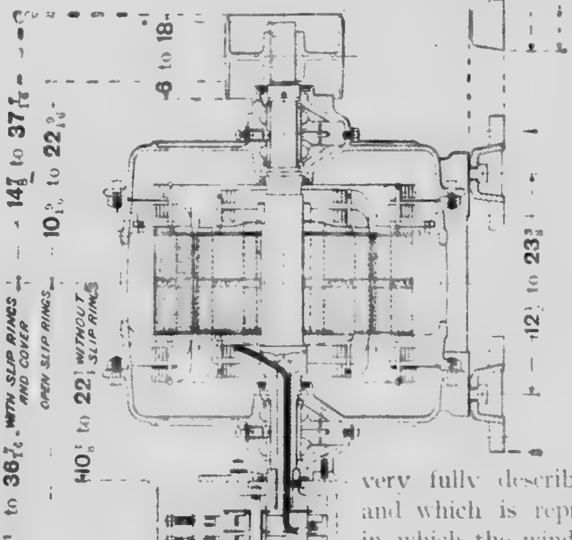

17¼ to 36¾ WITH SLIP RINGS AND COVER
14⅞ to 37 7/16
10 9/16 to 22 9/16 OPEN SLIP RINGS
10⅝ to 22¼ WITHOUT SLIP RINGS
8 to 18
12¼ to 23⅜

Fig. 704.

Bush Standard Polyphase Induction Motors.

whole of a single stamping, whilst Fig. 708 on a larger scale shows the slots and notches. The inner diameter of the stamping was 12⅞ inches, which was to be bored out accurately to 13 inches in the finished machine; the outer diameter was 20¾ inches, with six semicircular notches, each $\frac{7}{16}$ inch radius, by which the stamping was to be keyed to the housing. There were 72 slots, each $\frac{7}{16}$ by 1½ inches, with a $\frac{1}{16}$-inch thickness of iron between the inner end of the slot and the air-gap. The plates were 13 mils (0·013 inch) thick, papered on one side only, the end plates, however, being 62·5 mils ($\frac{1}{16}$ inch) thick. The plates were built up to a thickness of 8⅜ inches, measured parallel to the axis of the machine.

Fig. [illegible].—Stator [illegible] Standard Polyphase Induction Motor.

As showing some of the differences involved in altering the size of a machine, Fig. 709 gives the details of a stator stamping for a machine similar to the above, but with an output of 5 B.H.P. instead of 25 B.H.P. The reduction in the different dimensions should be carefully noted. The sizes of the slots have perhaps been altered the least, the change being from 1½ inches by $\frac{7}{16}$ inch to 1¼ inches by ⅜ inch, which is not great. Their number, however, has been

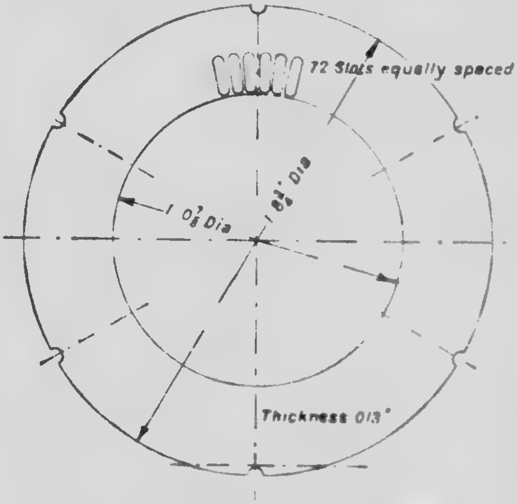


Fig. 707.—Stator Stamping for a 25 B.H.P. Motor.

reduced from 72 to 48; but even then the amount of cross-sectional space occupied by the copper is much greater relatively to the output than in the larger machine. The axial length of the laminated core is reduced from 8⅜ inches to 4¼ inches, or almost exactly to one-half

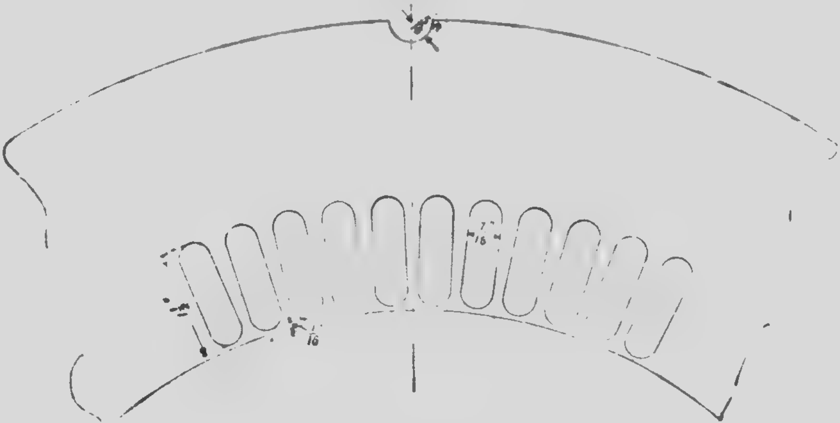


Fig. 708.—Details of Slots in Stator Stamping.

that of the larger machine. The enlarged detail at the side of Fig. 709 shows the windings in one of the tunnels for a line pressure of 220 volts.

The Rotor.—In the rotor part of the polyphase induction motor it is much more usual to have the slots partially or wholly closed than it is in the stator element. Referring to details already illustrated, we find in the drawing of the Bruce Peebles motor (Plate XII.) that the rotor slots are nearly closed. The details and dimensions of the stampings of the tunnelled rotor, corresponding to the stator, the stamping of which is given

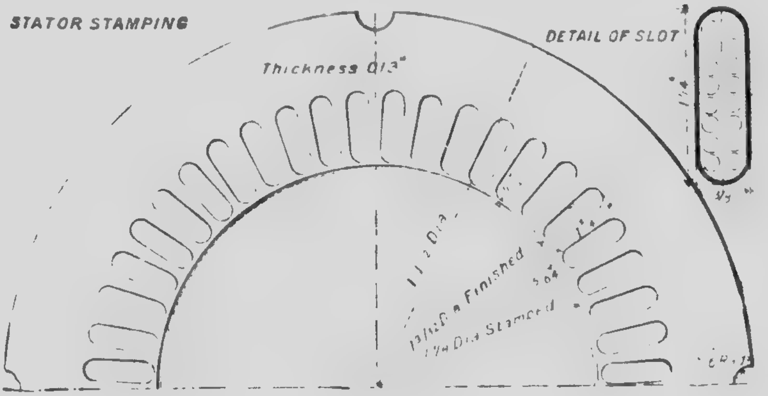


Fig. 709.—Half of Stator Stamping for a B.H.P. Motor

in Fig. 707, are given in Figs. 710 and 711. Fig. 710 shows the whole stamping, which was not carried by a spider, although it has a diameter of 13 inches, but was keyed directly to the shaft, ventilating holes 1½ inches wide being stamped out at about ½ inch from the shaft. The dimensions of the slots are given on a larger scale in Fig. 711; they were equal in radial length (1½ inches) to the slots of the stator (Fig. 707), but were a shade narrower, and only 54 in number as compared with 72 on the stator.

These figures and dimensions should be compared with Fig. 712, which gives the details of the rotor stamping of the 5 B.H.P. motor built by the same firm, the stator stamping of which was depicted in Fig. 709. In this rotor the discs were 31 mils ($\frac{1}{32}$ inch) in thickness, and the space for the copper winding or bars was provided by a series of circular holes, 31 in number and 137 mils ($\frac{9}{64}$ inches) in diameter. The stampings were solid down to the shaft, no openings being provided for ventilation in these small machines.

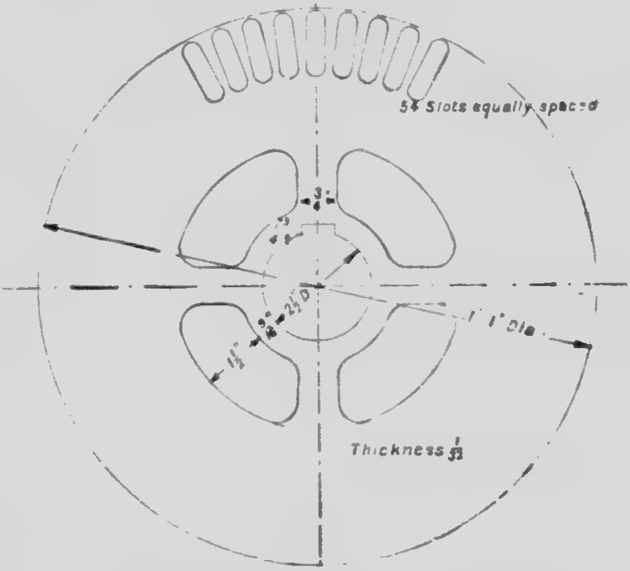


Fig. 712.—Rotor Stamping for 5 B.H.P. Induction Motor.

The plates in the larger rotor (Fig. 710) were also 31 mils in thickness, and it is worth noting that in both cases the stampings were more than double the thickness (13 mils) of the corresponding stator stampings. The reason is obvious when the general theory of the rotating field motor (pages 615 to 618, Vol. I.) is recalled, since eddy currents in the rotor are not so harmful as in the stator, and may, indeed, add something to the mechanical effect. As in the stator, both sets of stampings are screwed up with end plates 625 mils thick.

Attention may be directed here to the very narrow air gap allowed in these motors. In the smaller size, 5 B.H.P., the finished internal diameter of the stator was $7\frac{3}{32}$ inches, whilst the finished external diameter of the rotor was $7\frac{1}{16}$ inches; the air-gap therefore could only be $\frac{1}{64}$ inch, or 16 mils, wide, a condition which, as the motor had to run at 1,500 R.P.M., necessitated extremely accurate workmanship and practically made no allowance for the wearing of the bearings. To reduce the latter to a minimum the bearings were made of solid phosphor bronze, unlined with any softer material. As the shaft was made of the best steel it was claimed that the actual wear with efficient lubrication was practically nil. In the larger, or 25 B.H.P., size the gap, though not quite so narrow, was only 20 mils, or 0·020 inch, a clearance which, to ensure good running at 1,000 R.P.M., necessitates the same high-class workmanship and finish as in the preceding case.

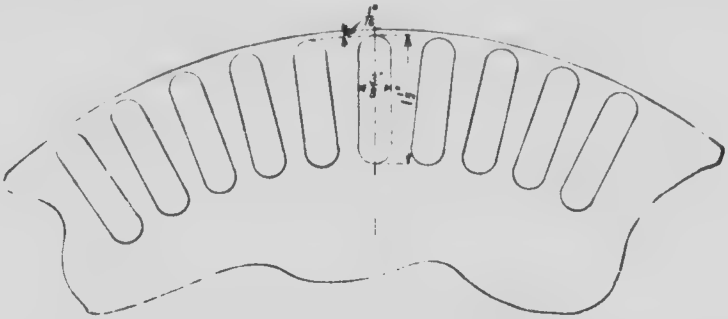


Fig. 711.—Details of Slots in Rotor Stamping.

Although the core plates in the cases above referred to are keyed directly to the shaft, this is far from being the usual practice, for many manufacturers prefer to build them on driving spiders in the manner so frequently followed with continuous-current armatures. Examples of cores so built have already been given in Figs. 593, 595, and 596 in Vol. I., and such examples could be multiplied almost indefinitely. Thus the rotor core plates of the motor in Fig. 701 are keyed to a five-armed spider, and a driving spider is also used in the Bruce Peebles induction motor (Fig. 698). The great advantage of the spider driving is the better ventilation which conduces to cool running, and this may be still further improved by fixing inwardly projecting blades to the spider, as in the Bruce Peebles rotor of Fig. 698, where three such fanning blades will be noticed.

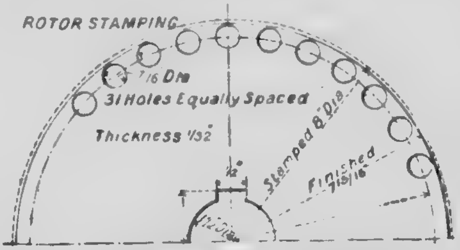


Fig. 712.—Rotor Stamping for a 50 B.H.P. Induction Motor.

Stator Winding.—The principle involved in the winding of the stators and rotors can be best followed by considering some actual examples.

First, in regard to the method of winding the stator apart from the actual connections, the open form of slot referred to at page 699, and illustrated in Figs. 701 and 702, has the great advantage that it allows "former"-wound coils to be more readily used than the partially closed form shown in Figs. 703 and 705 and elsewhere. The tunnel, or the very nearly closed, form of slot, requires that the wires or rods shall be threaded in from the ends.

The difference between the two methods of winding is well shown in Figs. 713 and 714, which are taken from machines of these different types. Fig. 713 shows the stator, the rotor, and one of the end frames of Messrs. Mather and Platt's P 90 induction motor. We are concerned at the moment only with the stator; the other parts will be referred to later (*see* page 708). The stator stampings are supported as usual in a rigid cast-iron housing, these stampings being open slotted to receive the windings. The coils of the latter are former-wound (*see* page 74, Section I.), and are finished to fill the slots with a minimum of pressure. The end connections will be obvious from previous descriptions of the windings of former-wound alternator armatures. The coils are dried electrically before assembling, and afterwards the whole is dried in a vacuum to ensure freedom from moisture. The ends of the windings are brought to terminals on the outside of the housing.

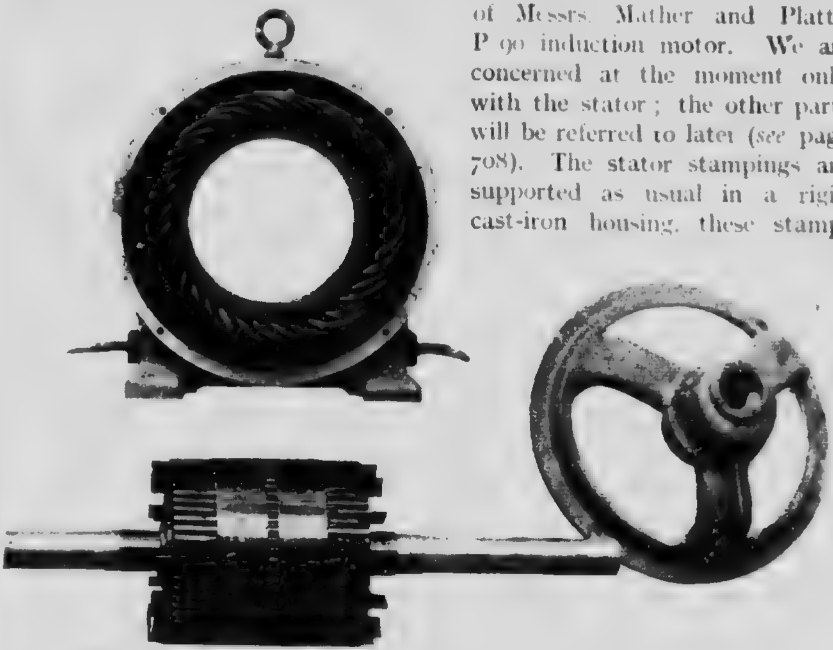


Fig. 713.—Stator, Rotor and one Endplate of Mather and Platt P 90 Polyphase Motor.

The other method of winding has already been illustrated in Fig. 706, which shows the stator of a motor built by the Brush Electrical Engineering Company, and in which it will be noted that the end connectors are very similar to the end connectors in the "barrel" or "cylindrical" type of armature winding for a continuous-current machine.

Another form of end connectors more usually adopted for the windings of a three-phase stator is shown in Fig. 714, which illustrates a smaller stator of the same standard series built by the same firm.

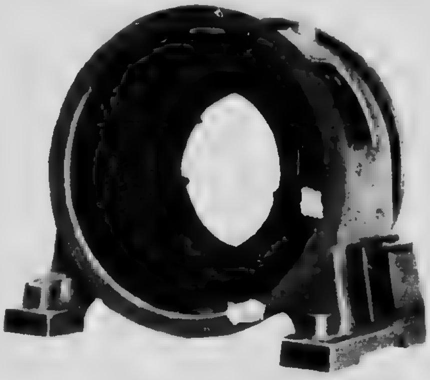


Fig. 714.—Small Stator, Brush Electrical Engineering Company.

The scheme of the winding in any one of the above cases follows the rules already explained (*see* Figs. 582 to 586, Vol. I.) for winding magnets to produce a rotating field with polyphase currents. One example only need be given here. Fig. 715 shows diagrammatically the winding scheme for the stator of the 25-B.H.P. motor, stampings for which have been given in Figs. 707 and 711. It is to be supplied with diphase currents, which will give a six-pole rotating field. The windings consist of twelve sets of coils, each occupying six of the seventy-two slots, and connected in two distinct circuits for the two phases. With a periodicity of 50 ∿ the synchronous speed of rotation of the field, according to the rule given on page 691, would be

$$\frac{60 \times 50}{3} = 1{,}000 \text{ R.P.M.}$$

Owing to the slip the actual speed of rotation of the rotor will be from 50 to 70 R.P.M. less. If required, the twelve coils could be connected on three circuits, which, when supplied with triphase currents, would give an eight-pole rotating field. In designing the winding of a stator it is a distinct advantage to have the number of the coils and of the slots twelve, or some multiple of twelve; for then, by only changing the connections, it can be adapted for either di- or triphase, or even monophase, currents, the speed of rotation of the field, however, being different in the two polyphase cases for the same periodicity.

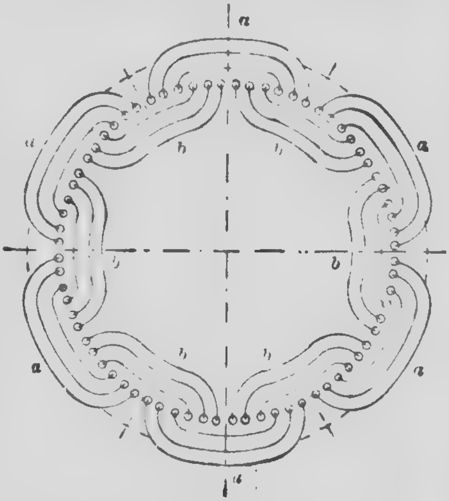


Fig. 715.—Windings of Six-pole Stator for Diphase Currents.

Rotor Winding.—As explained in Vol. I. (pages 618 to 620), the rotors of induction motors fall into two chief classes, namely, (*a*) the "squirrel-cage" rotors, in which single conductors, very lightly insulated, are placed in the slots and their ends connected either by two terminal rings or otherwise; and (*b*) the "wound" rotors, in which the conductors are wound on the rotor according to some systematic plan, and the windings either permanently short-circuited or brought out to slip rings, by means of which resistance, capacity, or inductance, as may be required, may be introduced into the circuits, or the rotor may be connected to another rotor, or may be otherwise dealt with.

Squirrel-cage Rotors.—The squirrel-cage rotor calls for very little further description. One standard type for large machines has been already described (*see* Fig. 697) in the account of the Bruce Peebles motors.

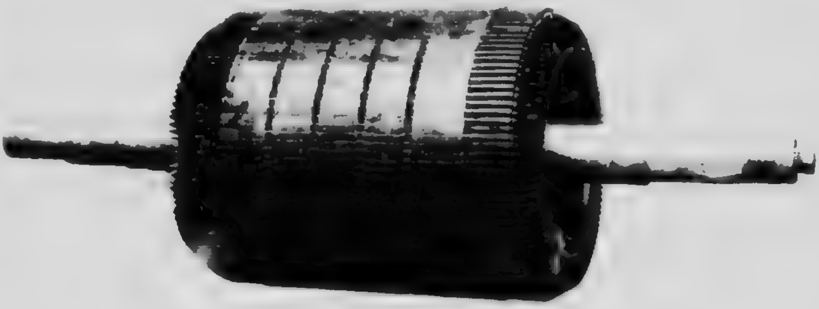


Fig. 716.—Squirrel-cage Rotor of Mather and Platt 400-B.H.P. Vertical Motor.

An early and good form of this type has also been illustrated in Fig. 592, and described at page 619 of Vol. I. A more modern pattern is shown in Fig. 716, which is a photograph of the squirrel-cage rotor of a 400-B.H.P. induction motor manufactured by Messrs. Mather and Platt. The ends of the heavy copper bars which are the conductors will be seen protruding from the two ends of the slots, which are very nearly closed. The short-circuiting copper rings are of much smaller diameter than the main body of the rotor, and are carried by the spider which supports the core plates or stampings. To these rings, one at each end, the ends of the copper conductors are connected by special connectors of strip metal so shaped as to act as fan blades, which when the rotor is rotating drive air into the central spaces, whence it escapes through the ventilating ducts; of these it will be noticed, there are as many as four, which are not excessive for a motor having so large an output. The sections of these connectors can be altered to meet the requirements of the motor load. It is interesting to note that this motor is designed to run with its shaft vertical. With a suitable auto-transformer starter (*see* page 722), it will start with about 50 per cent. of full-load torque with a line current of about twice the full-load current.

A much smaller rotor of the same type is shown in Fig. 713. In this rotor the core plates are keyed directly on to the shaft, there is one ventilating duct, and special fan blades project axially at intervals of about every five bars. The lubricating arrangements are shown in the figure; these are very important when a motor is required to run for long periods without attention. Ring lubrication is used, and an ample oil-well is provided in the hub of the end frame, which is of the "open protected" type.

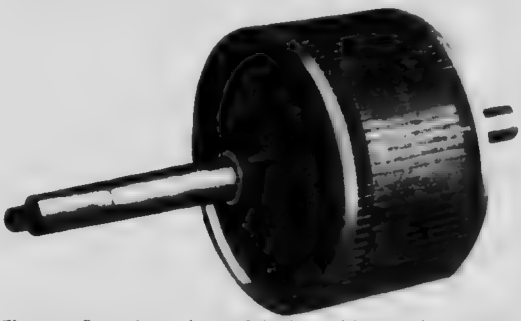


Fig. 717.—Squirrel-cage Rotor of the Brush Electrical Engineering Company.

Other standard types which will suffice to exhibit the variety of detail in the designs of different firms are shown in Figs. 717 to 719. Fig. 717 represents the rotor of the smaller sizes of squirrel-cage motors constructed by the Brush Electrical Engineering Company. The slots are half-closed and the stampings are clamped between end plates mounted directly on the shaft; there are no ventilating ducts between the core plates, but the whole core is pierced with large holes for ventilating purposes. The winding consists of copper bars lightly insulated from the core and riveted and soldered to short-circuiting rings clearly shown in the figure.

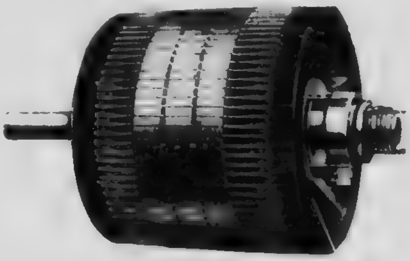


Fig. 718.—Squirrel-cage Rotor of the Lancashire Dynamo and Motor Company.

The standard squirrel-cage rotor of the Lancashire Dynamo and Motor Company is shown in Fig. 718. The stampings are keyed between end plates to a spider without the use of bolts, and ventilating ducts are left as shown. The copper conductors are of circular section, placed in partially closed slots and insulated. The short-circuiting end rings consist of a number of toothed annular discs stamped out of sheet copper. They can be seen in the figure below the projecting rods. The disc teeth form the connectors between the conductors and the rings, and ensure that the joint between each rotor bar and the rings shall carry only the current in that bar, the main rotor current being carried by the underlying rings. It is claimed that it is practically impossible for the joints to heat up and for the rings to work loose, whilst their large cooling surface keeps the rings themselves cool. The rotor resistance, and with it the starting torque, may be increased at any time by the removal of one or more of the short-circuiting rings.

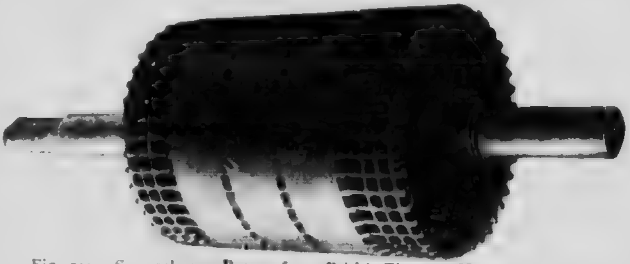


Fig. 719.—Squirrel-cage Rotor of the British Thomson-Houston Company.

Lastly, in Fig. 719 is shown a standard squirrel-cage rotor as constructed for large machines by the British Thomson-Houston Company. The slots are of the semi-enclosed type, and the conductors consist of straight copper bars which are laid in the slots, and are securely fastened to the short-circuiting rings; these are in multiple and provided with ample ventilating spaces through which cooling air is driven by the lugs. These lugs can be seen in the figure and act as fans, driving the air not only between the rings, but also through the core.

Wound Rotors.—Unless the starting voltage be specially reduced or some other device employed, the squirrel-cage rotor cannot be used for large machines because of the large starting current required, especially if it be desired to start under load, and because of the disturbing effect of this current on the voltage regulation of the system. Chiefly to obtain a good starting torque, therefore, without drawing an excessive current from the line, it must be possible to introduce resistance into the rotor circuits, and for this purpose the latter are wound according to some definite plan, and the ends brought to slip rings by which the necessary connections may be made. Several complete rotors of this type have already been depicted—e.g. in Figs. 505 and 506 (Vol. I.) and 608, *ante*—and it may therefore suffice to describe in detail the winding scheme of a particular rotor. For this purpose we select the rotor of the 25-B.H.P. motor, referred to in Figs. 710 and 711.

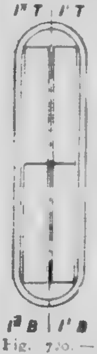


Fig. 720.—Position of Conductors in Tunnel of Rotor.

In this rotor there were four conductors per slot, arranged as in Fig. 720. The conductors were of copper 0·6 inch long and 0·11 inch thick covered with light insulation, so that the final dimensions were 0·615 by 0·125. It will be remembered that the slot (Fig. 711) was 1·5 inches long and 0·375 wide; there was, therefore, plenty of room for these conductors. In the following diagrams T stands for a top conductor and B for a bottom one, whilst a single dash indicates the conductor on the right, and two dashes a conductor on the left, as shown for No. 1 slot in Fig. 720. The winding is a three-phase "star" winding, and the key plan of the winding is given in Fig. 721, which shows the more important of the connections for the three circuits, which are denoted by (*a*) a continuous line, (*b*) a dotted line, and (*c*) a chain-dotted line respectively. The fifty-four slots are indicated by dots, and are numbered consecutively from 1 to 54 in a counter-clockwise direction. The connections shown in this diagram are, first, the connections at the junction point, which is represented by the circle J J, and to which the top right-hand conductors in slots 46, 16, and 22 are connected; secondly, the connections to the three slip rings, which again are made to the top right-hand conductors, i.e. slots 1, 7 and 31 respectively; and lastly, the reversing connections in the middle of each winding, which will be more clearly understood by reference to the developed winding for *one phase* which is given in Fig. 722, the phase dealt with being that shown by a continuous line in Fig. 721. In this diagram the slots are numbered 1 to 54 from right to left, the intervening teeth being indicated by section lines. As there are four conductors in each slot the diagram of the teeth is repeated to avoid confusion; the top part of the diagram, therefore, refers to one half of the conductors for this phase, and the bottom part to the other half, the slots selected being in six groups of three each, thus giving the six poles required. The connections are shown by the full and dotted lines above and below the range of slots and teeth; each connector is bent over in the middle, so that one half of it passes above and the other half below the connectors of the other phases; in the figure the top portion of each connector is shown by a full and the bottom portion by a dotted line, and the position of the conductor in the slot is indicated by the ends of the connectors brought up to it, and by the letters T T and B B.

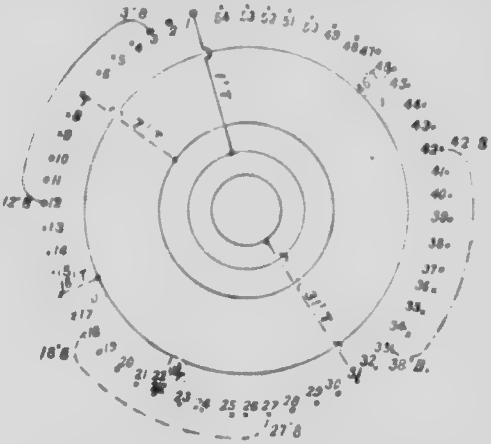
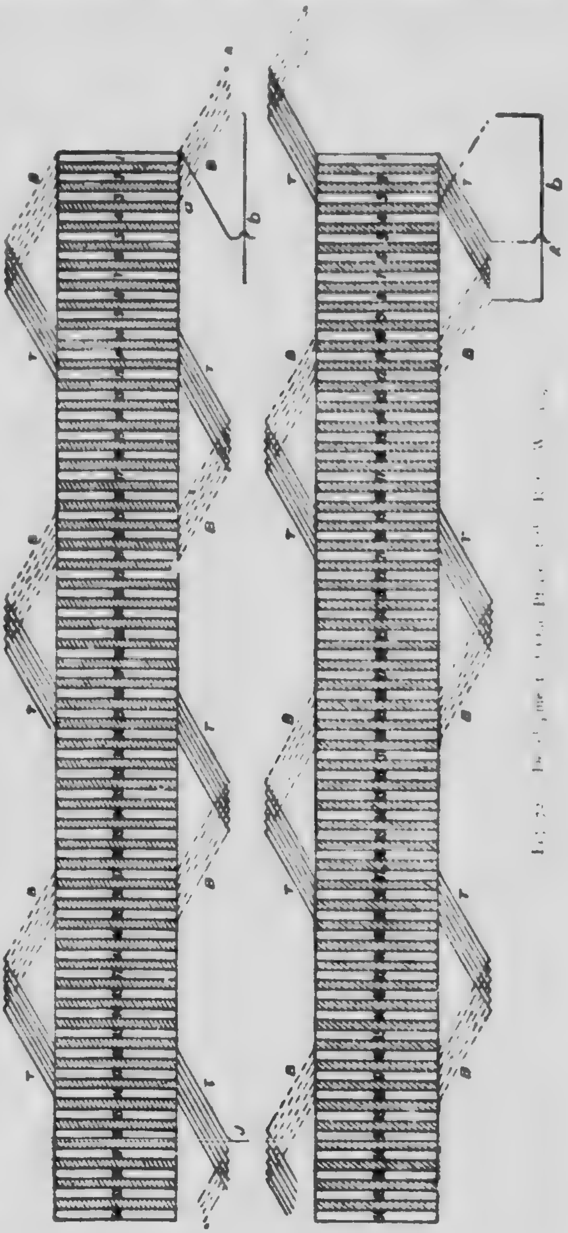


Fig. 721.—Key Plan of Three-phase Winding of Rotor.

We can now readily follow the course of the winding in the phase dealt with. Starting in the top range at the point J, which indicates the common junction point of the three windings, the first conductor indicated is 46′ T (*see* Fig. 721), and then consecutively 37′ B, 28′ T, 19′ B, 10′ T and 1′ B. As the figure is the development of a cylinder, slot 1, in passing from left to right, is followed by slot 54, and the connectors similarly pass on, for it will be noticed that the winding is a "wave-winding"; 1′ B is therefore followed by 46″ T, 37″ B, 28″ T, and so on, until by following out the plan we arrive at 3″ B and the point *a* on the right. Here the winding reverses, as shown by the key plan (Fig. 721), where a special connector differing from the others is shown joining 3″ B to 12″ B. This connector is shown by the line *b*, which is common to the top and bottom parts of Fig. 722, and the remaining half of the winding is now given in the lower part of this figure. Starting at 12″ B, it follows through 21″ T, 30″ B, 39″ T, 48″ B, 3′ T, and so on, until it finally emerges at 1′ T, to pass on through A to the slip ring. It will be noticed that by the reversal of the winding at *b b* the connectors for the last half of the winding fall into the gaps left by the connectors for the first half.



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It is not necessary to describe in detail the windings of the other two phases, but the reader who desires to understand thoroughly the principles underlying the design of the above winding should draw up from the diagrams a winding table suitable for use by the mechanic who has to wind the rotor in the workshop.

Whilst the above gives a winding scheme for the rotor of a three-phase induction motor, details of the end connectors, slip rings, etc., as worked out by well-known firms will be found in Figs. 723 to 726. Fig. 723 illustrates the standard wound rotor built by the British Thomson-Houston Company; the slots are of the semi-enclosed type, and the rotor is wound by hand, using former-wound coils fed through the opening of the slot. Before winding the covered wire is subjected to a vacuum drying process which abstracts all moisture and the wire surroundings at the end of this process are immediately saturated with an impregnated insulating material and are afterwards baked. The wound rotor is then vacuum dried, treated with an insulating varnish, and baked, the process being repeated once, twice, or three times, as may appear necessary, thus producing exceptional damp-resisting properties. The near end of the shaft in Fig. 723 is the slip-ring end, and is hollowed out to carry the insulated connectors passing between the slip rings and the windings of the rotor; these connectors can be seen passing into the shaft close to the spider and emerging from the end of the shaft. It is, of course, necessary, if the slip rings are to be outside the bearing, for the shaft to be so hollowed, for the wires could not pass the bearing on the outside of the shaft. As this end of the shaft, however, does not transmit any power, there is no mechanical objection to weakening it in this way. Another point to notice is the very heavy serving of binding wires by which the end connectors are held in their places; no binding wires are used over the iron core, the active wires being held in their places by the overhanging teeth and by the usual wedges. Finally, it should be noted that ample ventilating ducts are provided.

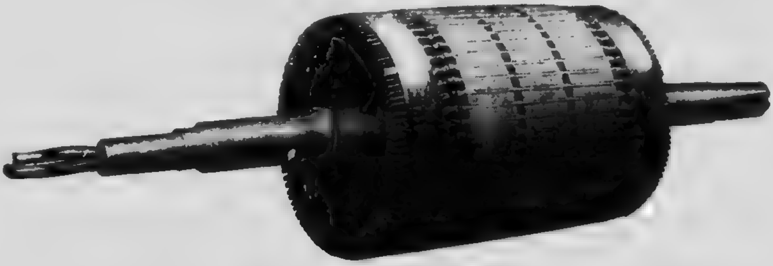


Fig. 723.—Completed Wound Rotor (Without Slip Rings) of the British Thomson-Houston Company.

Figs. 724 and 725 show for contrast the standard wound rotors of the Brush Electrical Engineering Company for small and large machines respectively. In these cases the illustrations show the slip rings mounted on the axles. The larger rotor, Fig. 725, may well be compared with Fig. 724, and the points of resemblance as well as those of difference noted. In Fig. 725 the conductors are copper bars and the details of construction are designed for heavy work, these rotors being intended to give an output up to 200 B.H.P. at 730 revolutions per minute. In the smaller rotor (Fig. 724) it will be observed that the scheme of end connectors is quite different, and that no binding wires are used, other means being adopted to hold the connectors in their places. In both figures the connectors between the slip rings and the windings can be seen emerging from the end of the shaft, and in Fig. 725 some of the details of their connections to the slip rings can be made out.

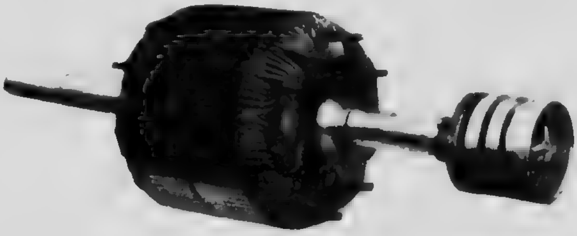


Fig. 724.

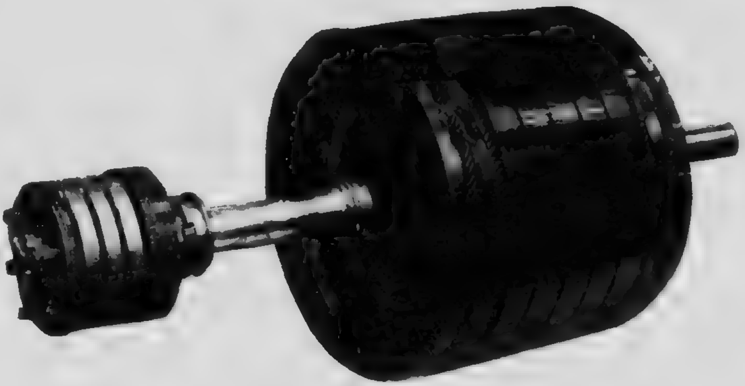


Fig. 725.

Wound Rotors of the Brush Electrical Engineering Company.

As a last example, Fig. 726 shows the complete wound rotor of the Lancashire Dynamo and Motor Company. In this case also the slots are partially closed, the core being built up as for the corresponding squirrel-cage rotor, and the coils are former wound. Ball bearings are used, and it is claimed that these, combined with good mechanical balancing and workmanship, make it safe to run with such a small air-gap that the magnetic leakage is appreciably diminished and the power factor increased. For instance, the balls used in the bearings are true spheres correct to standard size within 0·0001 of an inch. It will be noted that cooling fans are provided at each end of the rotor.

In all schemes for the winding of an induction motor an important point is the relative number of slots in the stator and the rotor, and the numbers are usually chosen so that the ratio is not a simple one. In fact, they are sometimes, though not necessarily, incommensurable. Referring to some of the motors described above, we find that these numbers in the small rotor shown in Fig. 701 are 54 to 41, which are incommensurable, as is also the case with the 5-B.H.P. motor of Figs. 709 and 712, where the numbers are 48 and 31. With wound rotors the ratio may be simpler, because of the more definite directions given to the rotor currents by the windings. Thus, in the Peebles motor (Fig. 692) the ratio is 96 to 72, or 4 to 3, and in the 25-B.H.P. wound motor (*see* Figs. 707 to 710) it is 72 to 54, also 4 to 3. Suppose, for instance, that the slots in the stator and rotor were equal in number, and the rotor were standing still with both sets of slots radially in line; on passing current through the stator winding the combination would act as a static transformer, of which the rotor would be the short-circuited secondary, and would not tend to turn in either direction, for it is obvious that there is no reason why it should start in one direction rather than in the other.

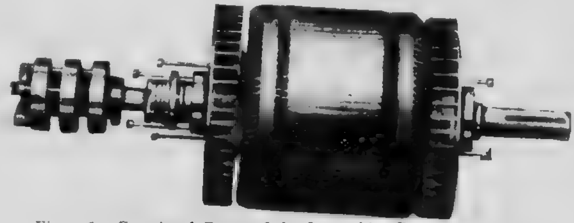


Fig. 706.—Completed Rotor of the Lancashire Dynamo and Motor Company.

Squirrel-cage *v.* Wound Rotors.—In comparing the practical results of these two methods of designing the rotor of a polyphase induction motor it is obvious that, from the point of view of the user, the squirrel-cage motor is almost ideal. It has the advantage of simplicity, it is cheaper and easier to operate, whilst its cost of upkeep is negligible, since there is nothing to get out of order or to require renewal. When once started also and running under a good load it has a higher efficiency and power factor, whilst its overload capacity is greater. The outstanding point against it is that it must be started with little or no load, and even then special starting devices are necessary. If it be started under load it takes a heavy starting current at a low power factor, and the starting torque is small, as we shall explain in a subsequent section. These difficulties are not so serious with small as with large motors, and therefore some manufacturers only build small squirrel-cage rotors, whilst for large sizes wound rotors are standard practice.

II.—THE STARTING OF POLYPHASE MOTORS

Although the main subject of this section is the starting of induction motors it will be convenient here to devote a few brief preliminary paragraphs to the starting of synchronous motors.

Synchronous Motors.—These motors, as already explained, are reversed alternators, running without slip at a dead-constant speed determined by the frequency of the supply current and the number of poles on the machine. Like alternators, they must, of course, be separately excited.

Where the motor, as one member of a coupled plant set, drives a continuous-current dynamo, arrangements are usually made to start up the set from the continuous-current side by using the dynamo temporarily as a motor, with the usual starting devices which have been fully described elsewhere in this book. When the alternate-current motor approaches full speed proper synchronising devices, as explained elsewhere, must be used before it is switched on to the alternate-current supply mains. The field excitation can then be adjusted to give the power factor required. If the motor has a direct coupled exciter and can be started quite light, and also if a supply of continuous-current energy of the proper voltage is available, the exciter may be used as a starting motor, the exciting current being temporarily taken from the continuous-current mains.

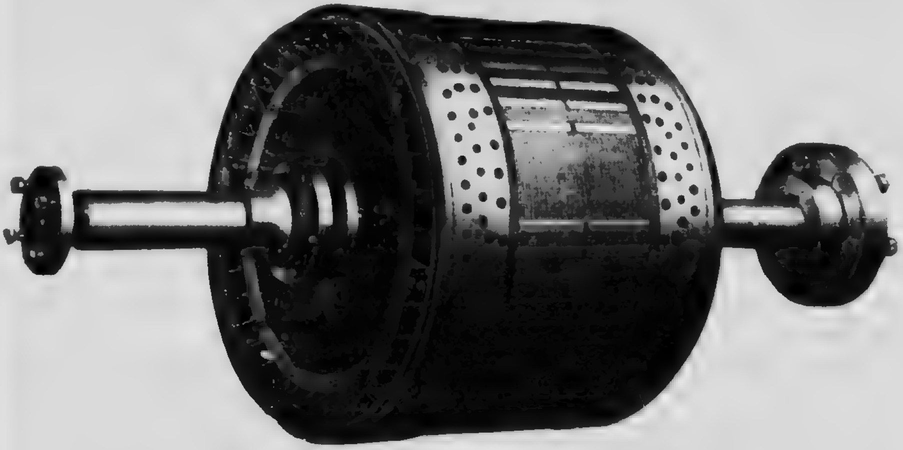


Fig. 727.—Field Magnet of Self-starting Synchronous Motor

If, however, neither of the above or any similar method can be used, a special starting machine must be used. This often takes the form of a small direct-coupled induction motor usually carried on an out-bearing on the shaft, and of sufficient temporary output, frequently one-sixth of that of the big machine, to start up the motor and bring it up to synchronous speed, when, after being synchronised, it can be thrown on to the mains.

Self-starting Synchronous Motor.—It is, however, possible to combine the induction starting motor with the synchronous motor in a single machine, and the Lancashire Dynamo and Motor Company have designed a type of synchronous motor which can be its own induction motor for starting purposes. It is a reversed revolving field alternator, the field magnets being of the non-salient pole cylindric type, as shown in Fig. 727. The terminals of the revolving field magnet are necessarily brought, as usual, to two slip rings, and when the stator is thrown on to polyphase mains the usual rotating stator field of an induction motor is set up. If now the slip rings be connected through starting resistances a single-phase alternate current will be set up in the circuits of the field magnet shown in Fig. 727, which thus becomes the wound rotor of an induction motor, wound, however, for monophase currents. The connections of the starter are shown in Fig. 728. It is a 13-position rheostat, with about half the resistances arranged to act as starting resistances for the induction motor and the other half to cut down the continuous current of the exciter. On position 1 the whole starting resistance is in series with the rotor winding, and, the main stator switch (not shown) being closed, the machine starts as an induction motor, the exciter E being out of circuit. The starting resistance is cut out step by step to position 6, on which the rotor is short-circuited, and the machine comes up nearly to synchronous speed with the usual small slip. At position 7 a transition buffer resistance is inserted, and at 8 the exciter E is placed on the slip rings with all the resistance in series with the rotor, which is now a four-pole field magnet. The motor automatically takes charge of the slip R.P.M., and pulls itself up to synchronous speed, after which the exciter current can be adjusted to its required running value.

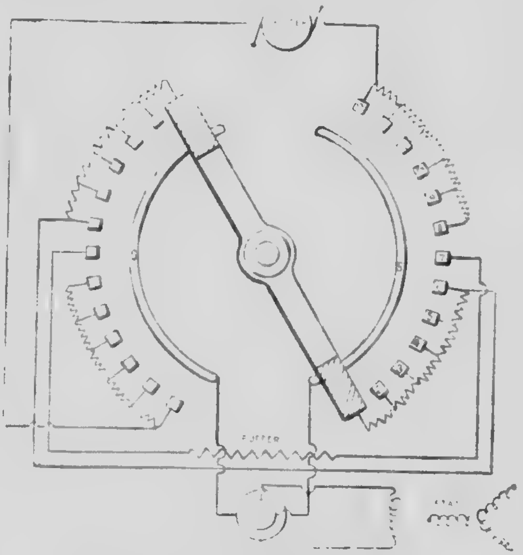


Fig. 728.—Starter for Synchronous Motor.

As regards the field magnet or rotor winding, it is interesting to note that it is well ventilated with numerous air ducts, and with deflector plates on the end zones to drive air through the rotor. The coils are of flat copper strip wound on edge in special formers and then taped up, dipped in an insulating compound, and dried. They are afterwards placed in troughs of prepared insulation, and held in place with wooden or insulated bronze wedges. The end connections are still further secured by special bracings.

The stator (Fig. 729) is of the alternator armature type fully described elsewhere. Machines have been built up to 750 H.P. to run at 750 R.P.M. on 2,200-volt three-phase mains. They practically solve the problem of a self-starting synchronous alternate-current motor, and can be used as "phase-advancers" (*see* page 1312).

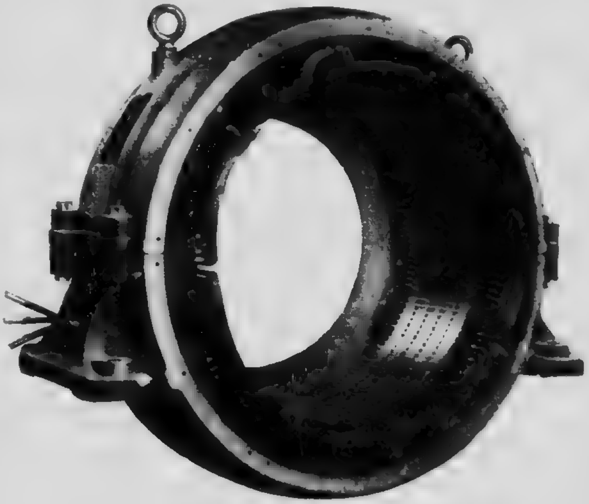


Fig. 729.—Stator of Self-starting Synchronous Motor.

Induction Motors.—As with continuous-current motors, so also with polyphase induction motors, certain precautions must be observed in starting the motor from rest, whether loaded or unloaded. Some of the possible methods of starting may be briefly summarised as follows :—

(1) By throwing the motor direct on to the mains.

(2) By altering the connections of the stator windings—

  (*a*) From a running "mesh" connection to a starting "star" connection.

  (*b*) By a series-parallel rearrangement of the stator coils.

(3) By supplying to the motor at starting a voltage less than the full running voltage.

(4) By throwing the motor direct on to the mains, but simultaneously introducing resistance into the circuits of a wound rotor.

(5) By modifying the construction of the motor so that it may be thrown direct on to the mains when starting. The chief modifications used have been—

(*a*) A two-part stator with one part movable relatively to the other (Boucherot).
(*b*) A two-part stator with a phase-changing transformer in circuit with one of the parts (Boucherot).
(*c*) A specially constructed squirrel-cage rotor (Boucherot).
(*d*) A rotor so wound and arranged that at a definite speed the connections are changed from starting to running connections (Gorges and Hobart).
(*e*) Multiplex windings on the rotor successively short-circuited as the speed increases.
(*f*) A variable magnetic circuit in the rotor (Zani).

It will be noticed that the first three of the general methods scheduled above deal with the stator circuits only, as these circuits are ordinarily wound, and are therefore applicable, at least theoretically, to all forms of polyphase induction motors. The fourth method, however, which requires the introduction of a starting resistance into the rotor circuits, cannot be applied to squirrel-cage rotors and necessitates that the rotor should be wound and its terminals brought to slip rings. In fact, it may be said that it was this method of starting which was the chief cause of the development of the wound type of rotor. The methods scheduled under (5) are all special methods requiring specially constructed machines.

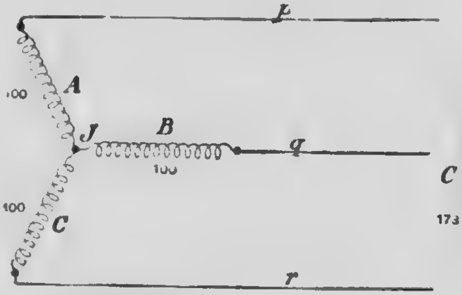


Fig. 730.—Voltage on "Star" Connections (Starting).

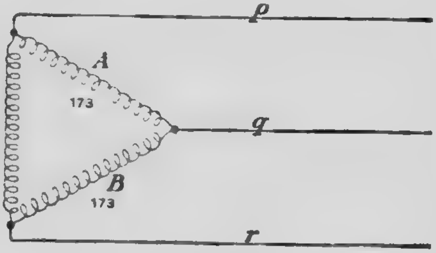


Fig. 731.—Voltage on "Mesh" Connections (Running).

The first method (1) cannot be used with impunity on any but small motors, and then only when the motor is started light or on no load, unless the motor has a specially constructed rotor or some protective automatic device. If an attempt be made to start a large ordinary motor or a small one heavily loaded in this simple way a very large current will flow through the stator; and not only will this current be large, but it will have a considerable lag, or, in other words, a low power factor. The consequences of such a current being drawn from the mains may not be confined to the motor which is being started; in addition, the heavy lagging current demanded may introduce serious phase differences and voltage disturbances into the network from which it is drawn, and, as a result, interfere with the regular running of other motors in the neighbourhood. Such a crude method of starting should therefore not be employed except for quite small or for specially constructed motors.

The "Star-mesh" Method of Starting.—This method, also known as the "Star-Delta" and as the "**Y**-Delta" method, consists in winding the polyphase stator for its phases to be connected in "mesh" for running purposes, but with their terminals brought out so that they may be connected in "star" for starting purposes. This change, which can be made by a simple throw-over switch if the currents be not too heavy or the voltages too high, reduces the starting voltage at the terminals of each stator coil, as will be evident on an inspection of the diagrams in Figs. 730 and 731, which apply to a three-phase motor. In both diagrams the supply mains are represented by p, q, and r, and a constant alternate-current voltage, say of 173 volts, is supposed to be maintained between them; A, B, and C are the windings of the stator for the separate phases. In Fig. 731 this line voltage between p and q supplies current to the coil A only, whilst in Fig. 730 it supplies current to the coils A and B in series. Because, however, of the star connection J in Fig. 730, the currents in A and B are not in phase, and the pressure across the terminals of each of these windings is 100 volts; the two coils in series, account being taken of the phase differences, absorb the 173 volts from the mains. Put otherwise, the alteration of voltage on the individual windings on changing from mesh to star is equivalent to working with 58 per cent. of the line voltage.

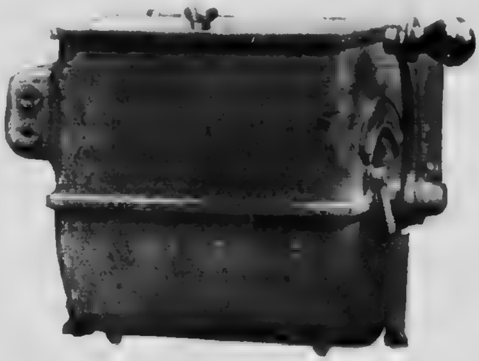


Fig. 732.—Y-Delta Oil-immersed B.T.-H. Starting Switch.

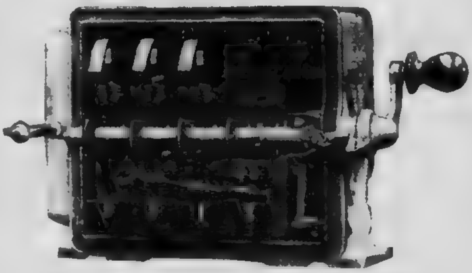


Fig. 733.—B.T.-H. Starting Switch as seen from beneath.

Special switches are available for making the above change, a well-known example being the "**Y**-delta switch" of the British Thomson-

Houston Company. The external appearance of this switch is shown in Fig. 732. It consists of an upper portion, containing the terminals and fuses, whilst the lower portion is a semicircular oil tank containing the contacts of an oil switch. The under part of the upper portion is seen in Fig. 733, which is a view looking at the switch from below, the oil tank having been removed. The **U**-shaped contacts into which the blades of the switch enter, and the copper sparking fingers, which take the final break, can be readily made out. The switch is worked by the handle at the right-hand side, which has three positions, and the actual change of the connection made by the switch can be ascertained by an inspection of Figs. 734 to 737. In the central position the switch is "off"; if pulled towards the operator the connections are made in the starting or "**Y**" position, and when pushed hard over from the operator it is in the "delta," or running position. In Fig. 734 the large rectangle represents the base plate with the contacts in position, these contacts being marked by little squares. The knife switch has four blades insulated from one another, but moved simultaneously by the one handle; L_1, L_2, L_3 represent the incoming live wires, which are brought one to each of three of the blades. The terminals of the three stator coils are marked A A_1, B B_1, and C C_1 respectively, A_1 being brought to the fourth of the knife blades. The dotted lines show the cross-connections within the switch and the three pairs of crossed lines represent the protecting fuses. When the switch is in the "off," or central, position (Fig. 736) only the knife blades are alive, and all other contacts are dead, even if the main switch (not shown) be closed. In the next position the contacts are joined as in Fig. 735; L_1, L_2, and L_3

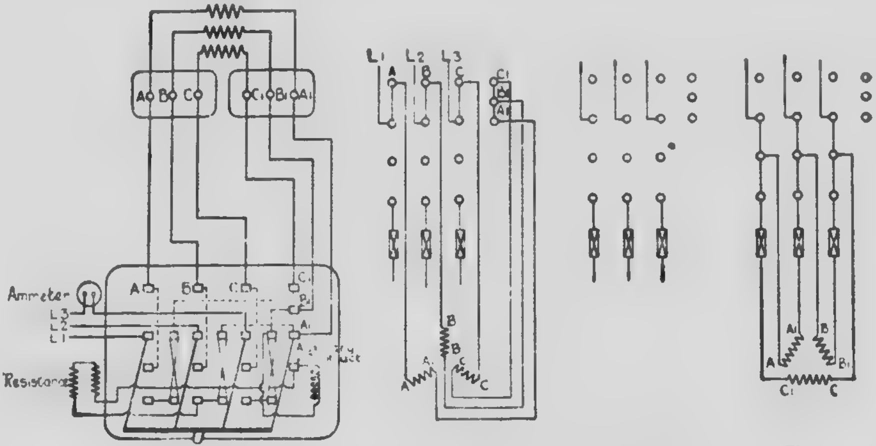
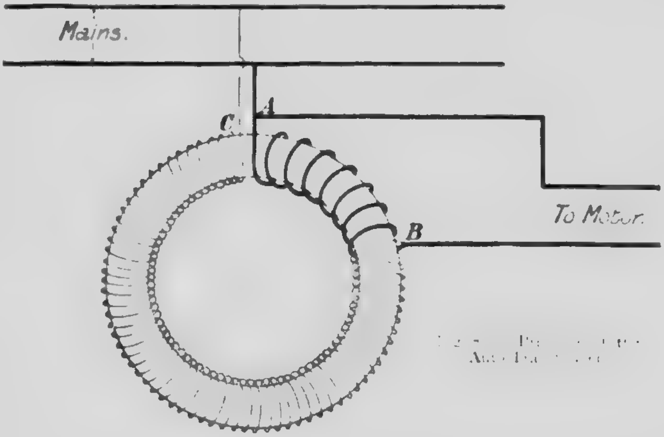


Fig. 734. Fig. 735. Fig. 736. Fig. 737.

Connections of B.T.-H. Oil-immersed **Y**-Delta Starting Switch.

are put on to A, B, and C respectively, and A_1, B_1, and C_1 are joined by the fourth blade, forming the neutral point of the **Y**; the fuses are not in circuit. This is the "starting" position. In the third or "running" position the contacts are as in Fig. 737; the stator coils with the fuses in circuit are joined in "mesh" or "delta." The fourth blade of the knife switch is idle, except for voltages above 400–500, when it is utilised (Fig. 734) to introduce a low-voltage release solenoid with bridging resistance between A_1 and B_1. The system of interlocking is very complete, for the switch cannot be thrown from the off to the running position without passing through the starting position. Also the top lid seen in Fig. 732 cannot be opened to get at the fuses, etc., unless the handle is in the off position, and vice versa, when the lid is open the handle cannot be moved from the off position until the lid has been closed. Lastly, the low-voltage release device is enclosed in the oil-switch casing.



[illegible]

More recently the same makers offer an air-break "**Y**-delta" switch for motors up to 25 B.H.P. at 550 volts, containing all the usual safety devices and practically fool-proof.

The Series-parallel Method of Starting.—This method consists in dividing up the windings of each phase of the stator into a number of equivalent sections, connected in series in each phase for starting purposes and in parallel for running purposes. Theoretically there is no limit to the number of sections which may be used, but in practice only two separate sections are wound in each phase. When placed in series instead of in parallel on the mains the voltage at the terminals of each winding is reduced to one-half the line voltage which is supplied to the coils when running on load in parallel. The effect, however, of this diminished voltage, as will be shown presently, would be to reduce the starting torque to one-quarter of what could be obtained with full line voltage. With each winding in two sections four terminals per phase must be brought to the starting switch, which, therefore, has to handle twelve terminals with a three-phase motor.

Starting with Reduced Voltage. The third method of starting polyphase motors, referred to on page 717, consists in supplying for starting purposes a voltage lower than the running voltage of the machine. This can be done in several different ways. The most obvious is to throw into the stator circuits a resistance in series, to absorb part of the pressure, leaving only the balance for the motor. The method is, however, wasteful, and should only be used for small motors where the resistances required would not be costly, and where the power wasted would not be serious.

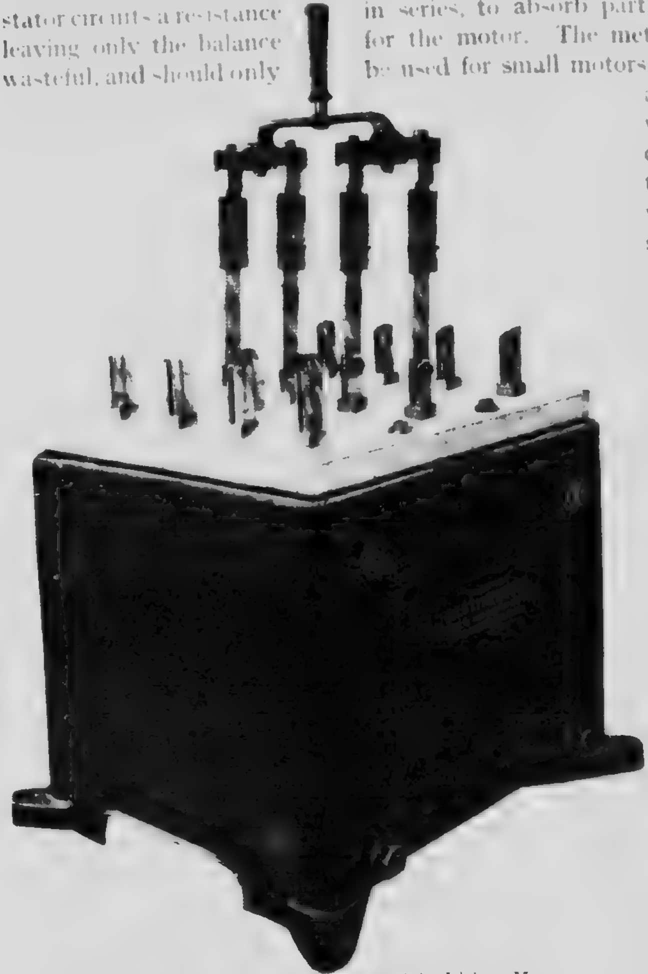


Fig. [illegible].—Westinghouse "Auto-Starter" for Diphase Motor.

A much better method is to use an auto-transformer, the principle of which is shown in Fig. 738. A core of laminated iron, as in any ordinary transformer (cf. pages 433 to 442, Vol. I.), is overwound with a single coil, the ends of which A and C, are to be joined to the mains. This coil is tapped at some convenient intermediate point B between A and C, and the motor is connected to the points A and B. The mean P.D. between A and B is necessarily less than the mean P.D. between A and C. This would also be the case if a mere coilless and inductionless resistance were connected to the mains between A and C; but in the auto-transformer, in addition to the resistance action, the part of the coil between A and B acts as the secondary of a transformer, with reference to the whole coil as the primary. Thus it is possible to draw a much larger current from the terminals A and B than is flowing between the mains at A and C. To carry this larger current, the turns between A and B are represented in the figure as made of thicker copper than the turns between B and C carrying the smaller current. In this way a large current at a correspondingly low voltage can be supplied to the motor. In Fig. 738 only a single phase is dealt with; the necessary additions for polyphase working are obvious.

The "auto-starter," as it is called, of the British Westinghouse Electric Company works on this principle and is shown in Fig. 739. The pattern illustrated is intended for diphase motors, and consists of a double-throw copper switch with four contacts on each side. Below the switch-base are two auto-transformers with their reduced pressure terminals connected to the contacts on one side and the full-pressure terminals connected to those on the other. The levers of the switch are connected to the four terminals of the diphase motor. For starting, the chopper is thrown on to the low-pressure terminals, the mains having been connected with an ordinary switch or otherwise to the high-pressure terminals. When the motor has run up to speed the chopper is thrown over on to the full-pressure terminals. By moving the point B (Fig. 738) to different positions on the winding the starting voltage can be adjusted to vary the torque until the best conditions for the particular case are attained.

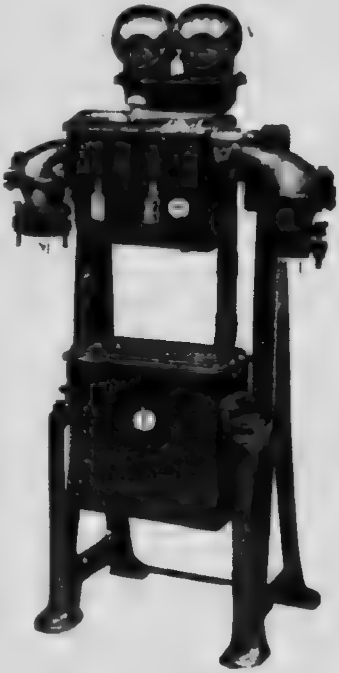


Fig. 739.—The [illegible] Auto-Starter.

A neat form of "Auto-Starter," illustrated in Fig. 740, has been designed by Mr. George Ellison, of Birmingham. In this starter the transformer is carried in a separate oil tank T, mounted on the same brackets as and below the oil-immersed switch gear in S. The arrangement promotes facility of inspection for repairs and cleaning and economy of oil, as the oil in a switch chamber should be more frequently changed than the oil in a transformer tank; it also diminishes the possibility of explosion, as the transformer oil, which may become hot, is thus separated from the sparking contacts; further, the transformer may be removed entirely while the switch is in service.

The apparatus is for three-phase working, and the connections are given in Fig. 741. The three-phase supply cable marked L is led into the dividing box L (Fig. 740), in which its three parts are separated and led through a proper gland into the oil box S to the switch studs L_1, L_2, and L_3 (Fig. 741). The three-phase motor cable is similarly connected to M_1, M_2, and M_3 through the dividing box M. When the switch is thrown into the "starting" position these six studs are connected respectively to the contacts A, B, C, T_A, T_B, and T_C, the first three placing the line on to the coils of the star-connected transformer, and the last three placing the motor on to the particular transformer tappings which have been connected up. The diagram shows the connections on to the 0·5 or 50 per cent. tappings. When the motor has run up to speed the switch handle is thrown over from the "starting" to the "running" position, in which the central row of studs in Fig. 741 is connected to the lowest row of contacts. This completely cuts out the transformer and connects the L_1 and L_3 line phases to the M_1 and M_3 motor phases through the overload coils O_1 and O_3 respectively, and the L_2 line phase to the M_2 motor phase through the ammeter or ammeter shunt. The no-volt release shunt coil V_R is in circuit across the L_2 and L_3 line phases, and in Fig. 740 a voltmeter is shown across these phases. These three protecting coils are shown mounted on the front of the oil tank S in Fig. 740. They act in the usual way. The overload coils are adjusted to release the switch when the current in either of the phases connected reaches the value above the normal for which the tripping mechanism has been adjusted, and when this release

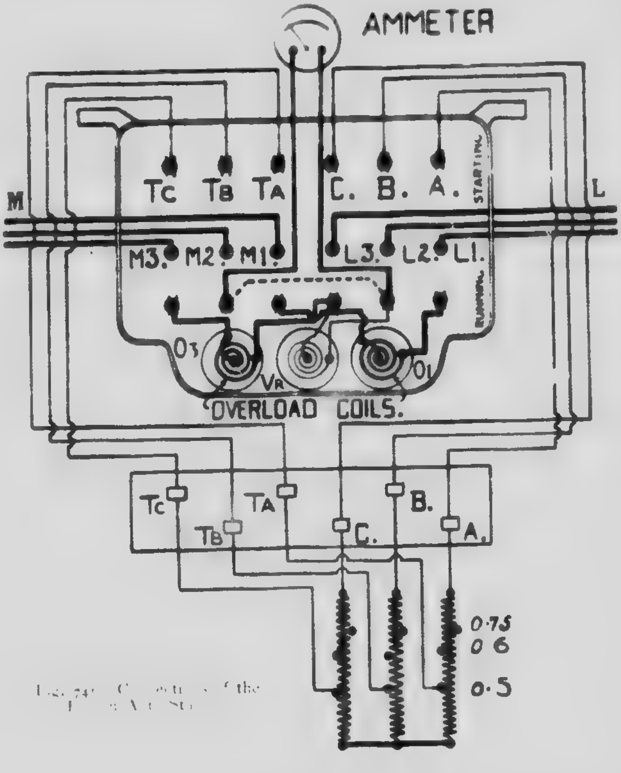


Fig. 741.—Connections of the [illegible]

occurs a powerful spring brings the switch to and holds it in the "off" position. The trip mechanism can also be operated by the no-voltage release magnet if the pressure drops to one-third of the normal or to zero by the supply failing.

From the "off" position the switch must be first placed in the "starting" position and held there before it can be thrown on to the "running" position; it cannot be left in the "starting" position, and if the operator were to let go the handle in this position the switch would immediately fly back to the "off" position. It will be noticed that in the starting position the automatic release magnets are not in circuit, as protection is rarely required during starting; if such protection is necessary, a separate circuit-breaker with automatic releases must be connected in the "line" circuits. Such a breaker is described on pages 1332 *et seq.*

The starter shown in Fig. 740 is for a 30-H.P. motor. A good modern induction motor of this size, if switched, when standing, on to the full voltage of the mains, would take about five times the full-load current and give about 1·5 times the full-load torque. On a 50 per cent. tap the starting current would be reduced to about 1·75 the full-load current and the starting torque to about 40 per cent. of the full-load torque. If the motor has to start against a nearly full-load torque a 75 per cent. tap would have to be used, and this would give a starting current about four times the full-load current. The standard tappings provided on these starters are 50, 60, and 75 per cent., and any one of these may be joined up for starting purposes; the determining factor is usually the load against which the motor is required to start.

In diphase working a reduced voltage for starting purposes may be obtained by taking advantage of the fact that the pressure between successive lines is less than the full pressure of either phase separately. With an appropriate switch similar to that shown in Fig. 739, but without the auto-transformers, the connections can be so made as to supply this reduced pressure to the motor for starting purposes.

Starting Torque.—The effect of reducing the voltage at the terminals of the stator for starting purposes is that the starting torque is thereby considerably reduced, as shown below, and the motor can only start under light or no load. Roughly, it may be said that the change in the starting torque varies as the square of the voltage. This method for motors which have to start under load is therefore not so good as the method which will be described presently of introducing resistance into the rotor circuit, by which it is often possible to get a full-load torque with about a full-load current; such a method, however, is only applicable to wound rotors.

As already explained, the standstill or starting torque and current of an induction motor connected direct to the supply main with a short-circuited rotor are much in excess of the full-load torque and current. and therefore there is a considerable margin to work upon with respect to the starting torque so far as the reduction of the starting voltage is convenient. This will be evident from the following table, published by the British Thomson-Houston Company for the different sizes of their squirrel-cage motors:—

Table VII.—Starting Torques and Currents of Induction Motors.

Horse-power	Mean Starting Torque in Terms of Full-load Torque	Mean Starting Current in Terms of Full-load Current
½ to 1	1·25 times	4 times
2 ,, 5	2·25 ,,	5 ,,
6 ,, 10	2·0 ,,	5 ,,
11 ,, 20	1·75 ,,	5 ,,
21 ,, 40	1·5 ,,	5 ,,
41 ,, 100	1·25 ,,	5·5 ,,
101 ,, 150	0·8 ,,	5·5 ,,

In connection with this table the Company has published also the curves given in Fig. 742. to enable the starting current to be found when using any of the standard percentage taps on their starting auto-transformers or compensators. the percentage referred to being, as already explained (*see* page 725), the percentage of line voltage which is applied to the terminals of the motor. In these curves the various figures for either torque or current on full-line voltage given in the second and third columns of the above table for the sizes of motors specified in the first column are plotted horizontally, and the starting torques or currents for various percentages of reductions in the voltage are plotted vertically to two different scales as specified; each curve has marked on it the percentage tapping to which it applies. Thus if an 8-H.P. motor be in question, and it be placed on a 70 per cent. tap, the starting torque, which is twice the full-load torque on full voltage, will be found to be 0·97 of full-load torque; whilst its mean starting current is reduced from five times the full-load current to a little over 2·4 times that current.

Energy losses are, of course, involved in the use of an auto-transformer as a voltage reducer for starting purposes. For instance, the transformer acts as a mere resistance, and so dissipates energy, but the amount so dissipated is chiefly on the A B section (Fig. 738) and is small. In addition, it absorbs wattless kilovolt amperes on account of its magnetising current and reactance. It is, however, easy to prove that the energy losses are very much smaller than are involved in the cruder method of reducing the voltage by starting resistances introduced into the primary circuit. For instance, in some experiments with a 20-H.P.

motor the energy taken from the line at starting when rheostats were used was four times the rated load of the motor, and whilst the motor absorbed 2·25, the resistances absorbed 1·75 times the energy of the rated load. With an auto-transformer tapped to reproduce the same starting conditions, the transformer only absorbed 18 per cent. of the rated load, reducing the power drawn from the line to 2·43 times the rated load. The magnetising current in the transformer was found to be less than 10 per cent. of the full-load current and its wattless reactance practically negligible.

Starting with Resistances in Rotor.—The fourth method (4) on

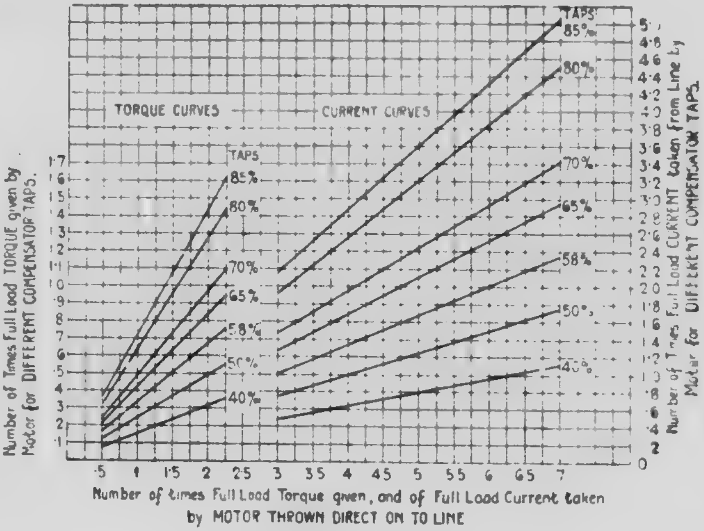


Fig. 742.—Effect of Using Compensation Taps.

page 717 is one which is very widely used since the introduction of resistance into the rotor circuits not only has the effect of cutting down the stator current and diminishing its lag, but also very materially increases the torque on the rotor; in fact, making certain approximate assumptions, it may be shown that at starting the torque is proportional to the resistance of the rotor circuit. As we know (*see* page 502, Vol. I.) that the torque depends on the product of the current and the magnetic field which it intersects, this result at first sight seems curious and contradictory, for the introduction of a resistance into a circuit, other things being equal, must necessarily cut down the current. The explanation lies in the phase relations of the various quantities involved. In exactly the same way, as we have already seen at page 801, Vol. I., that the product of a lagging current by the impressed E.M.F., giving the power in watts, involves as a multiplier the cosine of the angle of lag between the two quantities, so it may be shown that the product of any two directed quantities or vectors involves the cosine of the phase difference expressed as an angle in the usual way. In the present case and as tending, perhaps, to increase the mystery, the E.M.F. induced in the rotor conductors is for the same magnetic flux at its greatest when the rotor is stationary, for then the lines of force of the rotating field obviously cut the rotor conductors most rapidly. This large E.M.F. will set up large currents in a short-circuited rotor, especially of the squirrel-cage type, because of its low resistance, though here again the reader must remember that it is not the impressed E.M.F. alone (*see* Fig. 517, Vol. I.) which determines the current In fact, because of the large inductance of the rotor, relatively to its resistance, the angle of lag $\left(\tan^{-1} \frac{pL}{R}\right)$ is nearly 90°, and its impedance is great. Now, the stator current, as in a static transformer, is nearly in the phase opposite to that of the rotor current, and the quantity $\frac{pL}{R}$ is also large for the stator circuit. The impressed voltage required to send the current through the stator conductors is, therefore, nearly 90° in front of the current, and an additional voltage has to be provided to counterbalance the back volts caused by the rotating field, which are in opposite phase to the impressed volts on the rotor. These two voltages are therefore nearly in phase, and the resultant P.D. i [illegible] on the stator is therefore leading on the current nearly 90°, gi [illegible] heavy lagging currents already mentioned under (1).

Now suppose the rotor resistance to be materially increased, say to ten times its short-circuited value, the value of $\frac{pL}{R}$ in the rotor immediately drops to one-tenth its previous value, and the lag is considerably reduced. The rotor current moves nearer in phase to its impressed E.M.F., and the phase of the stator current moves with it, but not so far, the small resultant of the two, which is approximately the magnetising current, remaining fairly constant and unaltered in phase. Thus the voltage required to drive the current through the inductance and resistance of the stator gets out of step with the back volts, due to the rotating field, and the resultant of the two—that is, the P.D. impressed on the stator—is more nearly in step with the stator current. We thus get less lag in the stator circuits. Further, the diminished lag of the rotor current has increased the cosine of the angle between it and the rotating field flux much more than the amount by which the current itself has been diminished. The product of the three—i.e. current, field flux, and cosine of phase difference —which is proportional to the torque is therefore increased, and we have finally not only a diminished lag and current in the stator, but also an increased torque on the rotor. The demonstration by which this result has been reached, though somewhat long, should be carefully studied.

We now see the reason for attaching slip rings to some of the rotors (Figs. 724 to 726) described above. The method of using these rings in a given case is shown diagrammatically in Fig. 743, in which connections are taken from the supply mains through appropriate fuses F to the triple pole switch S_1. From this switch the working leads are carried directly to the terminals of the motor M. An entirely distinct set of leads starts from the slip rings *r*, *r*, *r* of the motor to the triple arm triphase switch S_2. This switch has connected to its studs three sets of resistances R_1, R_2, and R_3, there being five studs shown, *a*, *b*, *c*, *d*, *e*, for each, and one slip ring being connected to the last stud of each set. When the switch is rotated, the three arms, being at a fixed angular distance apart, rest upon corresponding studs simultaneously, and as the resistances and their subdivisions in each set are equal, the resistances in each rotor circuit remain equal to one another in each position of the switch. The resistances of the switch are thus star-connected, the common junction being at the hub of the rotating arms; these arms are shown in the starting position with all the resistances in

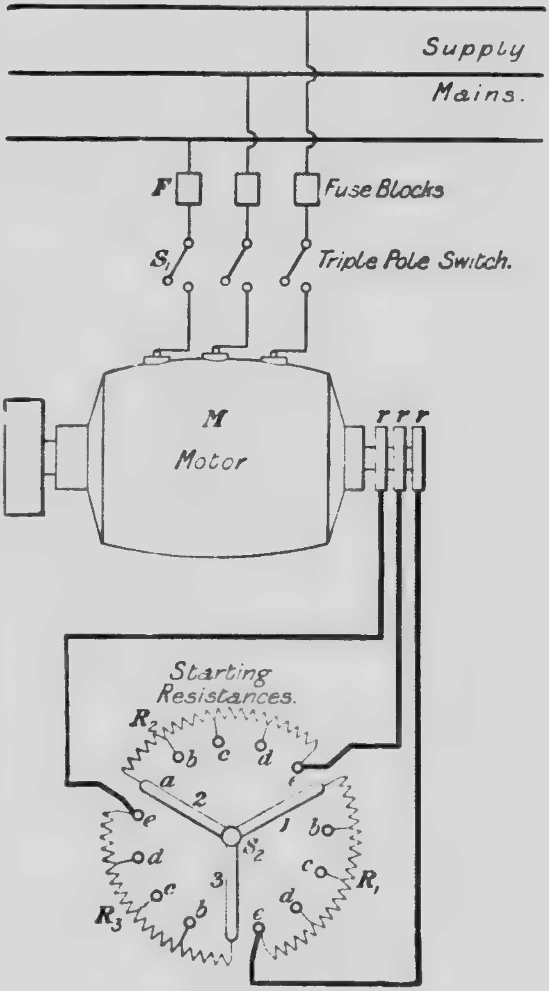


Fig. 743.—Starting of Polyphase Motors with Resistances in Rotor Circuit.

circuit. As the motor speeds up, the resistances are removed by rotating the arms in a clockwise direction, until finally, when they rest upon the studs *e*, all the resistances are cut out and the rings are short-circuited through the switch, leads and brushes. Many motors are provided with some device for short-circuiting the windings internally, and at this stage this device is brought into play and allows the brushes to be lifted off the slip rings, thus saving the energy, which otherwise would be lost in brush friction.

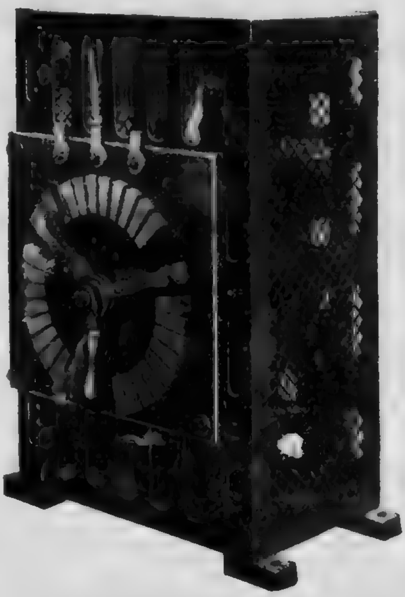


Fig. 744. Starting Switch for Triphase Rotor.

Starting and Controlling Switches.—The actual switches and resistances ordinarily used for introducing the requisite resistance into the rotor circuit fall into two chief classes in which the resistance material is of metal and of liquid respectively. In the first case, wire or grid resistances are usually attached to the studs of a three-arm switch such as is shown in Fig. 744, which is taken from such a switch constructed by the British Thomson-Houston Company. By moving the handle of the switch the contact fingers simultaneously pass over the studs of the electrically distinct sets of resistances, and thus alter the resistance of each circuit simultaneously by equal amounts. The switch illustrated is intended to be used in the rotor circuits of motors of from 40 to 100 B.H.P. The coils, therefore, have ample carrying capacity for heavy currents, and the protecting cover is pierced with numerous holes to promote ventilation and to keep the coils cool.

A rotor starter provided with automatic releases, designed by Mr. George Ellison, of Birmingham, is shown in Fig. 745 with the protecting cover and the operating handles removed. The operating handle projects through the cover and rotates the three arms, which by their position regulate the amount of resistance in circuit as already explained. The figure shows the axle in the " off " position with the rotor circuits broken and held in this position by a powerful spiral spring. In starting the motor the switch is moved slowly in a clockwise direction over the various contacts, reducing the resistance on the rotor circuits step by step until it is all removed and the rotor short-circuited. The brushes sweeping over the resistance studs are bolted directly to the metal of the rotating arms. In addition to operating thus on the rotor circuits the switch acts as a main switch on the stator circuits. Three insulated double brushes carried on the arms of the starter connect the outer to the inner ring segments; the supply mains are joined to the outer segments and the stator leads to the inner. The switch, if released on any of its steps, will fly back to the "off" position, but at the end of its movement it is held by the catch seen below the no-volt release magnet. There are two automatic release coils, one A, a current or series coil, placed in one of the rotor circuits, when the switch is full "on." If this coil receive excessive current, its plunger is attracted and knocks off the trip which is holding the switch in the running position. In this case the switch flies to the "off" position, and the motor stops as the rotor and stator circuits are all broken. The catch can also be knocked off by the core of the no voltage release coil V. This coil is bridged across two of the leads of the stator circuits, and if it loses its current its core falls down and the catch is disengaged from the switch arm, with the results described above. To stop the motor in an emergency the catch can be knocked off mechanically by throwing over a small handle on the outside of the cover. The circuit of V can also be taken through a small break-circuit switch in any convenient position, thus giving "remote control" so far as the stopping of the motor is concerned.

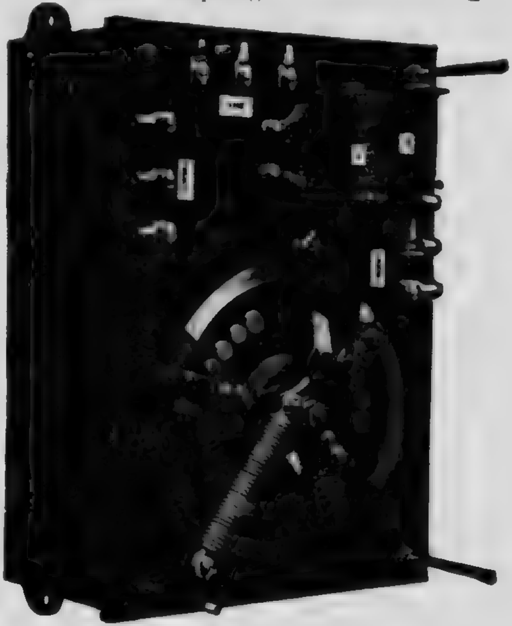


Fig. 745.—Ellison Automatic Starter

The placing of the overload release on a rotor circuit provides for the very possible contingency of one of the main fuses blowing. In this case, the motor could continue to run on the other two leads with an increased rotor current, which would operate the overload rotor release. If the overload coil were on the stator circuit it would for this case have to be adjusted to work with an overload current too little above the normal current to be comfortable for ordinary running, as it might give rise to frequent unnecessary stoppages. The no-volt coil, though across a stator phase, would not operate in this case, as the other phases would supply the necessary voltage to energise it. This coil is intended to operate only if the supply completely fails.

There is one case to which the above arrangement cannot be applied. This is when the motor itself is provided with gear for short circuiting the slip rings and lifting the brushes (*see* pages 735 and 736). In such a case the overload release must perforce be placed in one of the stator circuits.

An ingenious method of constructing a starting resistance for wound induction motors has been devised by Mr. H. M. Hobart. The requirements are that the resistance should diminish as the motor speeds up, and to obtain this result automatically and without any moving contacts Mr. Hobart utilises the well-known "skin" effect, which is more fully referred to elsewhere. If solid rods be used as conductors for alternate currents the ohmic resistance of such rods is greater for currents of high than for those of low frequency, owing to the unequal distribution of the current over the cross-section of the material. As the effect is an inductive one, it is much higher in iron than in non-magnetic metals. Experimenting with iron rods 1 inch in diameter and 14 feet long, it was found that the resistance, including contacts and leads, increased from 0·00234 ohm with continuous currents (0 cycles per second) to 0·0158 ohm (about 7 times) with alternate currents at 40 cycles per second.

Now it will be remembered that when the rotor is standing still the currents induced in it by the rotating field have the same periodicity as the latter, say 40 cycles per second. As, however, the rotor speeds up this periodicity diminishes until at synchronous speed it would vanish. Synchronous speed, as already explained, is never reached, there being always some "slip" which determines the frequency of the induced currents. Thus with a 5 per cent. slip the above frequency would be reduced to 2 cycles per second, at which periodicity the "skin" effect would practically vanish. The results of Mr. Hobart's experiments showed that with properly dimensioned iron starting resistances the requisite conditions for an automatic starter could be obtained.

A liquid resistance pattern of starting switch for rotor circuits is illustrated in Fig. 740, which represents a complete liquid starter and controller manufactured by Messrs. Allen West and Co., Limited, of Brighton, for use under the very severe conditions which have to be satisfied for haulage work in fiery coal mines, especially in Great Britain. The chief advantage of a liquid starter under such conditions is that in the removal of the resistance from the rotor circuit by diminishing the distance between the electrodes there is no danger of sparks, which might start an explosion; such sparks may, of course, occur in the switch illustrated in Fig. 743, for solid resistances as the sliding contact fingers pass from one block to the next. A further advantage is that when carefully designed to avoid certain contingencies—which will be referred to presently—the removal of the resistance can be made gradually and not in sudden jerks, as when a section of solid conductor is suddenly removed. Thus the speed from "creeping" to "full" can be increased quite evenly, and all unnecessary strains on the equipment avoided.

In Fig. 746 the whole apparatus is operated by the hand-wheel H, which, when moved in one direction or the other, first closes one only of the oil switches, M_1 or M_2, shown on the left-hand side. These are "main" or stator switches, and two switches are installed differently connected, so that the motor can be started in either direction at will. It has been explained elsewhere that if the connections to one of the phases be reversed, the revolving field, and therefore the rotor, will rotate in the opposite direction. The switches used are oil switches (*see* pages 567 to 574), the oil tanks being easily lowered, as shown by working the small hand wheel on the switch. They are heavily insulated, and can be worked with pressures up to 6,600 volts, the cables for lines and stator being brought through the sides of the top castings to terminals directly under the top removable cover. Until one of these switches is closed home

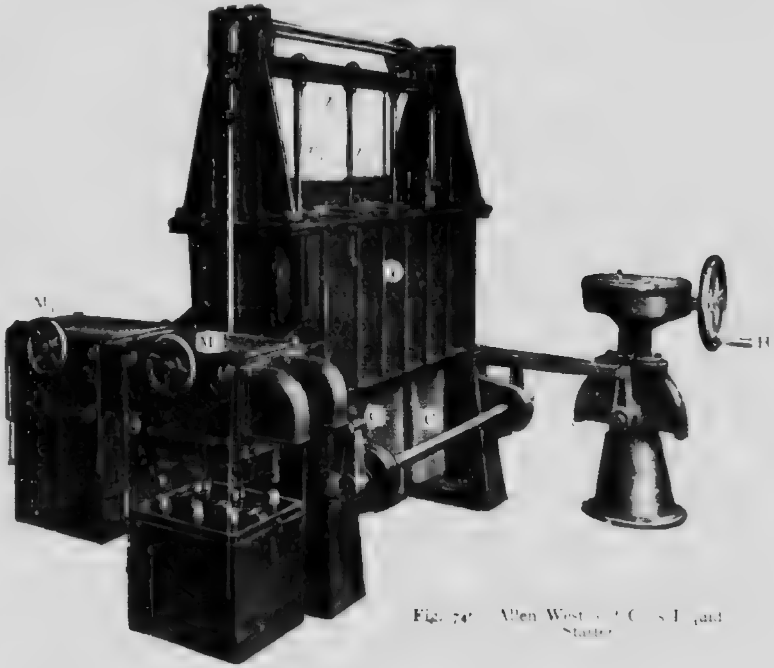


Fig. 746.—Allen West and Co.'s Liquid Starter.

the liquid resistances which are at their maximum value and in the rotor circuits cannot be altered from the starting position.

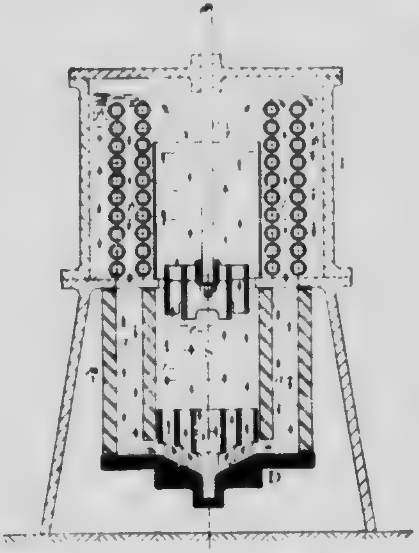


Fig. 747. Section of Tank of Liquid Starter.

The further rotation of the hand-wheel H mechanically reduces the liquid resistance in each rotor circuit simultaneously by lowering the upper electrodes. The resistance liquid is contained in a tank T, mounted over three chambers C C, made of glazed earthenware, a non-conducting material. One of these is shown in vertical cross-section in Fig. 747, in which T is the upper tank and t_1 t_2 the lower chambers for one of the resistances. The outer annular space *a a* is closed by a metal disc D, which carries a terminal for connecting the resistance to one of the brushes of the slip rings. Inside the inner chamber t_2 are the lower (fixed) and upper (movable) electrodes c_1 and c_2 respectively. The cast-iron electrode c_2 is carried by the rod r_1, which, passing through the top of the tank, is attached to a cross-head *h* (Fig. 746), which also carries the similar rods r_2 and r_3 of the other two chambers, and therefore is electrically the neutral point of the three-phase resistances, though the liquid in the upper tank also acts as a neutral connector. As the upper pistons c_2 (Fig. 747) are moved down, the resistance between the electrodes is diminished until the upper and lower come into metallic contact, when it is altogether removed and the slip rings are short-circuited except for the resistance of the connecting cables.

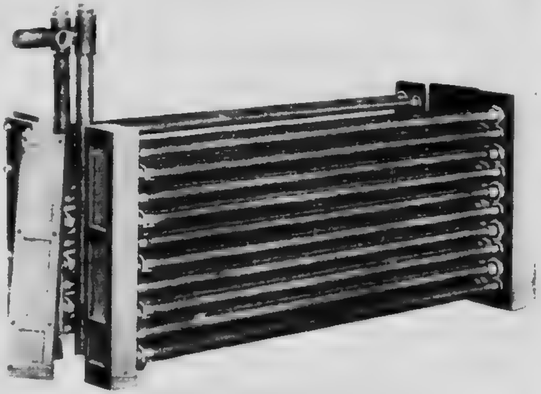


Fig. 748. Cooling Tubes for Liquid Starter

One of the difficulties to be guarded against in designing liquid resistances is the accumulation of electrolytic gas in the space between the electrodes as the presence of such gas increases the resistance between the electrodes, and by its intermittent escape causes this resistance to vary by jerks within what may sometimes be wide limits. This difficulty is overcome, in the design now being described, by special arrangements for ensuring the circulation and simultaneously the cooling of the electrolyte. The cooling is effected by the circulation of cooling water in the pipes (Fig. 747), which are shown separately in Fig. 748, and run through the whole length of the upper tank. The ohmic or c^2R heat produced between the electrodes e_1 and e_2 (Fig. 747) warms the electrolyte there, and this warmed liquid rises through passages in e_2 to nearly the top of the large tank. Simultaneously the liquid cooled by the pipes and contained in the space *p p* flows downward through the annular space *t t* between the two earthenware chambers, and then upward into the active space *s* between the two electrodes through passages in e_1. The circulation of the whole of the liquid is ensured by carefully placed baffle plates.

In conclusion, it should be mentioned that by a simple system of interlocking it is impossible to open the main switch M until the whole of the resistance has been reinserted in the rotor circuit.

The liquid used in such a starter is usually a weak solution of alkali, the drawback of which is its liability to form incrustations. An alternative is a weak solution of sulphuric acid, but if this be used special precautions must be taken to prevent it acting on any metal with which it may come into contact.

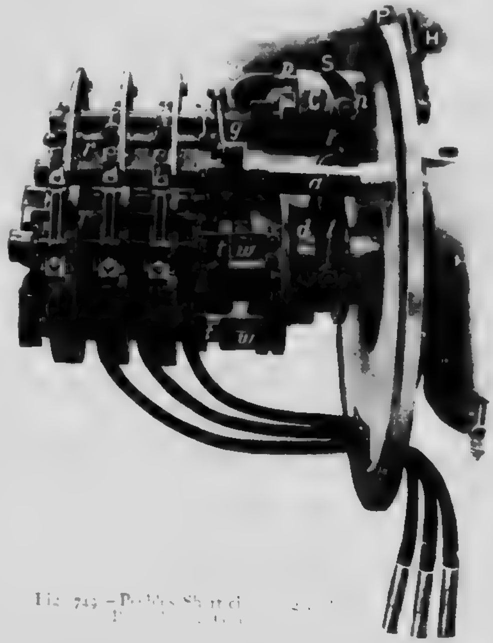


Fig. 749.—[illegible]

Short-circuiting and Brush-lifting Devices.—Whatever type of starting resistance be used, the short-circuiting device for running under load should be on the machine itself, so that the resistance of the leads should be cut out, and when the short-circuiting is completed the brushes should be lifted off the slip rings so as to eliminate their friction.

Many ingenious devices have been designed to accomplish these two objects whilst the machine is running, and we illustrate in Fig. 749 the gear designed by Messrs. Bruce Peebles and Co. to be used on the wound motors described on pages 691 to 696. The gear is operated by the handle H, which rotates an axle carried by the fixed plate P. This axle carries the cylinder C, on the surface of which is cut a screw-shaped slot S, which, when the cylinder is rotated, moves the pin *n* parallel to the axle of the machine. In Fig. 749 this pin is shown in its extreme position to the right. The pin *n* works the lever *ll*, which turns on an axle carried by the arm *a*, and whose lower end can move backwards and forwards the disc *d*, which is mounted on a sleeve carried by the running axle of the machine. This disc carries slotted contact jaws *w w*, which, in the position shown in the figure, slip over contact plates *tt* connected to the respective sets of brushes, thus short-circuiting them. Before these plates *tt* are driven quite home, but after the short circuit is fully established, a pin *p*, carried by the cylinder C, engages with the brush-lifting casting *e*, which is rotated slightly and by a system of links lifts all the brushes off the slip rings by means of insulated rods *r r*, which pass under the three brush arms in each case.

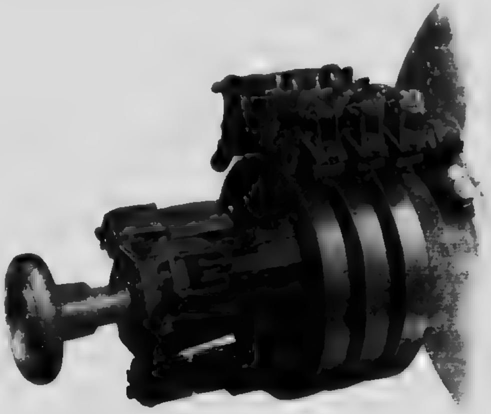


Fig. 750.—The British Thomson-Houston Short-circuiting Device.

The arrangement used by the British Thomson-Houston Company for short-circuiting the brushes when all the starting resistance has been taken out is shown in Fig. 750. By pushing in the handle which projects from the end of the shaft, the three contact clips, which can be clearly made out in the figure, engage with three contacts, each of which is connected to one of the slip rings, which are thus short-circuited. To this is added, when required, a device, not shown, for lifting the brushes off the rings by pushing in the handle still farther after the short-circuiting is completed.

Automatic Starting Panels.—By using contactors, as described later in the traction section, wound induction motors can be started by simply closing a switch in a separate controlling circuit. The necessary panels have been standardised, the methods being similar to those used in the traction section.

Motors of Special Construction.—In section (5) of the schedule given on pages 717 and 718 there are briefly indicated various methods of modifying the construction of a polyphase reduction motor with the object of securing the great advantage of being able to start the motor by simply switching it on to the full voltage of the supply mains. The schedule is not exhaustive, but actual machines, some of them of large size, have been constructed for each of the six methods so indicated. Unfortunately space will not allow us to give details and illustrations of the machines built, though these details are full of interest both from the practical and the theoretical points of view. For them the student should consult special treatises on the subject.

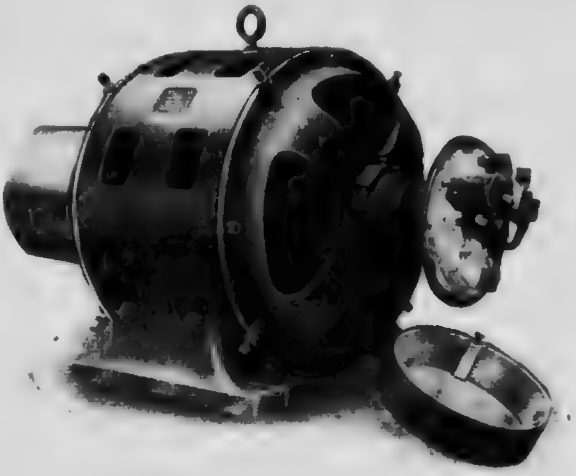


Fig. 751.—Bruce Peebles Motor with Automatic C[illegible]

As one example, however, of a machine built with a special automatic device somewhat similar to, but not the same as, that specifically mentioned in (5) (*d*), we give a brief description of an ingenious modification of the connections of the winding of the rotor, combined with a centrifugal starting device, designed by Messrs. Bruce Peebles and Co. The machine, which is shown in Fig. 751 with the starting device uncovered, has a rotor wound with four conductors per slot, and when the rotor is at rest these windings are so connected that the current in one of these conductors is directed oppositely to the current in the other three. This opposite current cancels the effect of an equivalent current in the three conductors, with the result that the conductors carrying the mutually cancelling currents act as a dead resistance to increase the resistance of the rotor, as is more usually done by using an external dead resistance. The rotor is thus able to start under full load current with a starting torque equal to 70 per cent. of the full-load torque.

As the rotor speeds up the centrifugal device shown on the end of the shaft in Fig. 751 acts when a definite speed is reached. This device is depicted on a larger scale and in greater detail in Figs. 752 and 753. Of these, Fig. 752 shows the position at starting and when the rotor is running below the speed at which the device acts, and Fig. 753 shows th running position [illegible] heavy block B (Fig. 752) is held against [illegible] the pull of the spring S, which can be set up to hold [illegible] position until the speed attains a certain desired value. At the [illegible] the block B, which is placed eccentrically, flies over against the [illegible] of S into the position shown in Fig. 753, thus closing the contacts at C and short-circuiting the windings of the rotor, which then [illegible] ordinary squirrel-cage rot[illegible] down the contacts [illegible] at a certain speed, and close at [illegible] ready for restarting.

The effect of this [illegible] device is shown in the curves of Fig. 754, which are taken from a [illegible] H.P. motor designed to run on a 3-phase

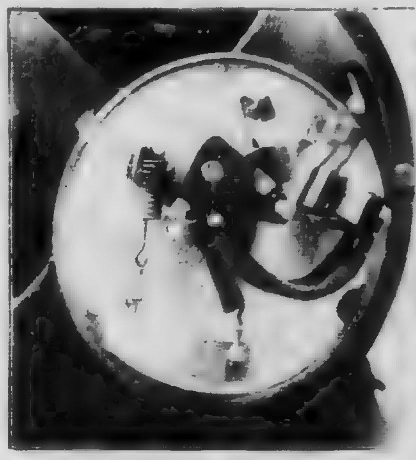
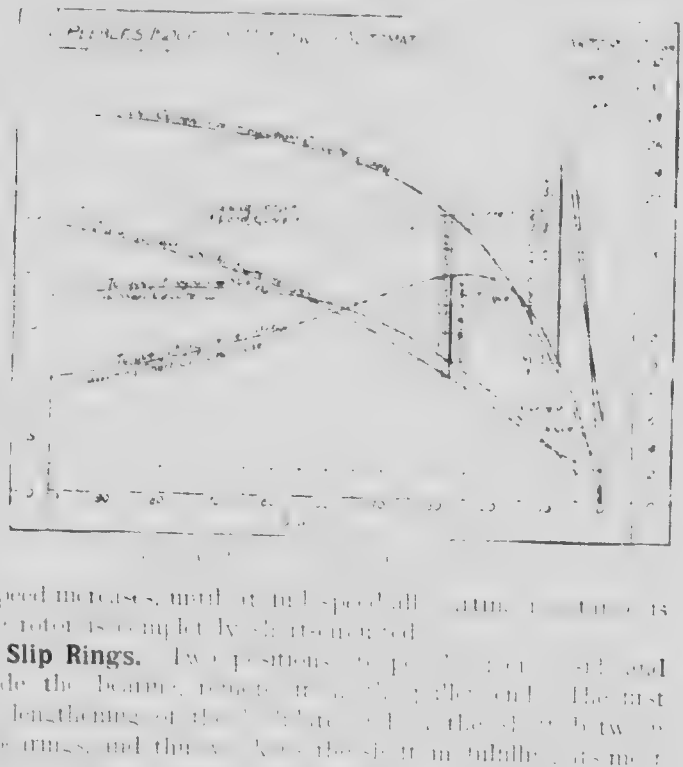


Fig. [illegible]

Fig. [illegible]

D[illegible]

500-volt [illegible] cycle supply [illegible] eight poles, [illegible] non-slip [illegible] starting switch [illegible] in the [illegible] represent the [illegible] the curve [illegible] curve on [illegible] torque curve [illegible] is made. [illegible] full-load [illegible] 20.5 [illegible] starting torque of 8 kilo[illegible] torque 14 kilogramme-metres [illegible] 7[illegible] per [illegible] curves C C and D D give the [illegible] current [illegible] B B respectively, the full-load current [illegible] starting current of 34 amperes, or [illegible] per cent. [illegible] shows a starting current almost [illegible] the [illegible] full-load current. [illegible] these curves are for the [illegible] the [illegible] 25 [illegible] slip [illegible] when the [illegible] through [illegible] torque [illegible] rise to [illegible] over the full [illegible] rapidly



[illegible] moving brush [illegible] have been out- [illegible] ward [illegible] contin[illegible]ly as the speed increases, until at full speed all resistance is cut out and the rotor is completely short-circuited.

Position of Slip Rings. Two positions [illegible] and the other outside the bearing remote from [illegible] end. The first necessitates the lengthening of the [illegible] between the two supporting bearings, and thus [illegible] the shaft in fulfilling its most important function of carrying the [illegible]. On the other hand, the slip rings are in a more protected position and the connections to the windings have not to be carried through the bearing, which necessitates a hollow shaft. If placed outside the bearing, the rings and brushes are more accessible but are also more exposed [illegible], and should be protected by special caps and coverings, which can be removed or opened up when necessary. The weight to be carried [illegible] the bearing is small and [illegible] of no consequence, but there is the disadvantage of the hollow shaft.

III.—THE WORKING OF POLYPHASE INDUCTION MOTORS

In the working of polyphase induction motors several interesting problems arise. In the preceding section on "starting," reference has been made to methods of improving the starting torque so as to enable the motors to start under load. The motor being supposed started, another important practical enquiry is as to the methods of speed control available, and their advantages and disadvantages, and also as to the variations of the torque when running under load at different speeds.

Relations Between Torque and Speed. Before dealing with the subject of speed control, a few further remarks concerning the relations between the mechanical and electrical quantities involved will tend to display some interesting peculiarities of this type of motor.

The mechanical quantities with which we are concerned are the efficiency, the power (B.H.P.), and its constituent elements torque and speed, whilst the electrical data are given by the amperes, the volts, the power factor, and the periodicity from which the speed of rotation of the field and the slip can be calculated when the number of poles is known.

An important connection is that between torque and speed, when the resistance of the rotor circuits is kept constant. This connection is given by Dr. S. P. Thompson in the continuous curve in Fig. 755.* in which the horizontal abscissæ represent speeds measured from left to right in the usual way, and the vertical ordinates represent the corresponding torques. The curve shows that starting from rest the torque O t_1, which is at first small, rises as the motor accelerates, until it reaches a maximum value, after which, if higher speed be required, it can only be obtained by sacrificing the torque, which rapidly diminishes until it sinks to zero at the point where the speed rises to that of the rotating field. At this point it is evident that there can be no torque, as there will be neither E.M.F.s nor currents in the rotor circuits.

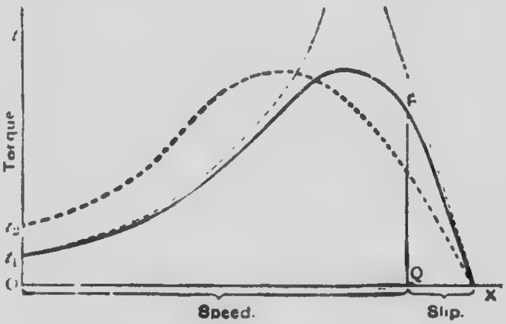


FIG. 755.—[illegible]

On the other hand, if when the motor is running at the speed corresponding to the maximum torque the load be altered and the torque suddenly decreased, the motor will speed up and thus the ideal speed control is not attained.

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* [illegible]

The dotted curve between t_2 and X shows the effect of increasing the resistance of the rotor circuit. The starting torque is considerably increased (in the case given it is doubled), and the curve rises to the same maximum as before; but this maximum occurs at a lower speed, and therefore the power obtainable is diminished. By removing the added resistance, which might be done when the maximum torque has been obtained, the speed can be increased without diminution of torque, and this process can be continued until the rotor resistance has been reduced to the lowest possible value by the coils being short-circuited.

If O Q be the speed at any time, the difference between it and O X, the synchronous speed, gives the slip Q X, and therefore, by measuring backwards from X towards O, any point P on the curves gives the connection between P Q the torque and Q X the slip, which plays a rather prominent part in the theory of the induction motor.

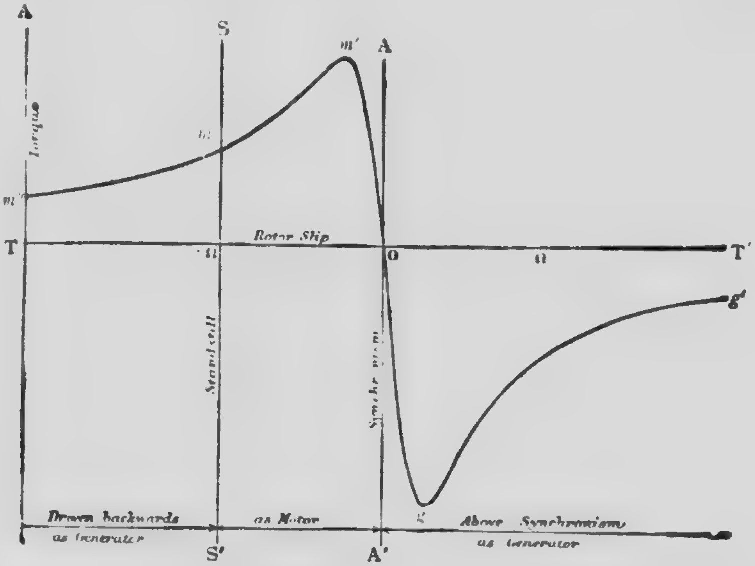


FIG. 756.—Steinmetz' Characteristic Curve of an Induction Motor.

The complete mechanical characteristic of an induction motor showing the connection between speed (or slip) and torque has been given by Steinmetz, whose curve is reproduced in Fig. 756. In this diagram T T' is the zero line for torque, all values above that line being positive and all below negative. Also S S' is the zero line for speed, all values of which, measured to the right from S S', are positive—that is, are in the direction of the rotation of the field—and all values to the left of S S' are negative, and signify that the rotor is rotating in the direction opposite to that of the field. When both torque and speed are positive their product is positive, and the machine is acting as a motor absorbing electrical power, and giving out mechanical power. But when one of these quantities is negative and the other positive, their product is negative, and the machine is acting as a generator, absorbing mechanical power and pumping electrical power back into the mains.

The point O marks the synchronous speed at which the field and the rotor are rotating with the same angular velocity. The space between O and Ω is the ordinary working region of the motor, and corresponds to X O in Fig. 755; the curve $m'' m'$ O is here similar to the curve t_1 P X of the previous figure. If, however, the motor be mechanically driven above the synchronous speed, so that the speed is marked off to the right of O, then the torque reverses, as shown by the curve O g g', and the machine runs as a generator, supplying power to the mains. Also, if the machine be mechanically driven backwards, so that the speed could be plotted to the left of Ω, the torque is given by the curve n m'', and, though positive, is directed oppositely to the rotation, and therefore the machine under these circumstances again acts as a generator and transfers energy to the mains. The whole curve is for one particular value of the rotor resistance, and its approximate symmetry about the lines T O T′ and A O A′ is very interesting.

The reader should compare the Steinmetz characteristic curve of Fig. 756 with the torque-slip experimental curves for the Bruce Peebles motor given in Fig. 754.

Speed Regulation.—One of the characteristic features of a polyphase induction motor is that when running under load the speed is nearly constant. It has already been mentioned that under such circumstances the slip or difference in angular speed between the rotating field of the stator and the rotating short-circuited rotor is very small, amounting to about 4 per cent. in well-designed machines. Now, the angular speed of the rotating field is fixed by the periodicity of the currents supplied and the number of poles and arrangement of windings of the stator; it is, therefore, in all ordinary cases a constant quantity. If, then, the speed of the rotor only differs from it by being a few per cent. less, that speed must be very nearly constant also, and experiment shows that such is the case with well-designed machines, which are found to run at nearly constant speed between full load and no load when the supply voltage is kept constant.

This property of the motors, admirable for many purposes, becomes a disadvantage when, as in tramcar work, they are required to run at various speeds under different conditions. Attempts have been made to control the speed by altering the voltage on the motor by means of variable taps on transformers; but the results are not satisfactory, as both the starting torque and efficiency become low if the voltage be altered much from the designed voltage. Other methods have therefore been sought after and developed, and to some of these we shall briefly refer

Control by Resistances in Rotor Circuits.—One of the most convenient methods of varying the speed of an induction motor is by introducing resistances into the rotor circuits. The effects of this method of control are shown in Fig. 757, which exhibits the results of tests made by the

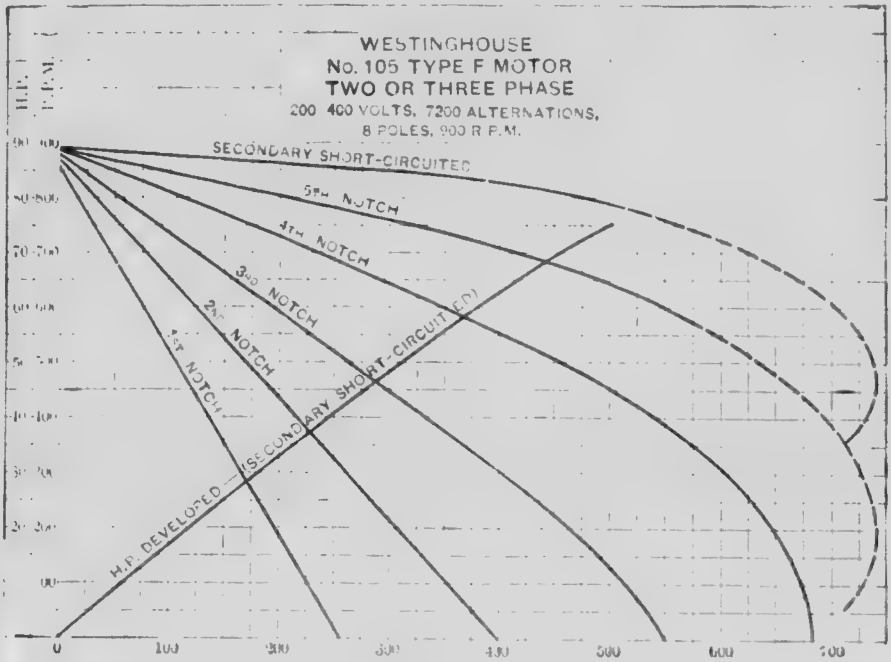


Fig. 757.—Experimental Characteristics, etc., of an Induction Motor

Westinghouse Company on a motor capable of developing a torque of 500 lb.-feet at a speed of 700 R.P.M., with its rotor short-circuited. The resistance is inserted in the rotor by means of a cylinder controller similar to the cylinder reverser of Fig. 654, but modified for the altered conditions. In the case before us the controller had six notches. The "first notch" introduces all the available resistance into the rotor circuit, and the line so marked is intended to give the connection between torque and speed for this resistance. As the controller is moved round notch by notch the resistance is diminished with each step, and the successive curves shown are obtained. Finally, at the last notch the rotor, or "secondary," as it is called on the diagram, is short-circuited, and the topmost curve gives the resulting mechanical characteristic.

For this case the horse-power curve is also drawn; it is nearly a straight line, but curves over a little for the highest powers, showing that the diminution of speed is beginning to tell more seriously than at lower powers.

The curves carry the theory of the motor further than Fig. 756; for whilst the two upper ones show, as before, that with increased resistance in the rotor the same maximum torque is reached, but at a lower speed, the lower curves show that if the resistance be increased too far, this maximum torque is not attained, and that the torque, starting at a much lower value, diminishes continuously with increase of speed. It would be interesting to continue these curves experimentally downwards into the region between A A′ and m'' T′ of Fig. 756.

The practical use of such curves is obvious, for they show that the motor can be started quietly under any load up to its maximum. Suppose, for instance, that it were required to start the motor under a load represented by a torque of 450 lb.-feet. On moving the controller on to the first, and then to the second notch, the rotor would not develop sufficient torque to move under the load, but on moving to the third notch a starting torque of 550 lb.-feet would be developed, and the motor would start and run up to a speed of 225 R.P.M., at which it would remain running with a torque of 450 lb.-feet corresponding to the load. On moving to the fourth notch the torque at this speed would increase to 640 lb.-feet, and the motor would again accelerate to a speed of 500 R.P.M., the torque again falling to 450 lb.-feet. These experiences would be repeated at the fifth and sixth notches, and at the latter the final possible speed of 810 R.P.M. under a torque of 450 lb.-feet would be reached, the H.P. developed being a little under 70. The nominal power of this motor is 50 B.H.P., which it will give when running at 850 R.P.M. under a torque of about 310 lb.-feet. The slip is then 5.5 per cent.

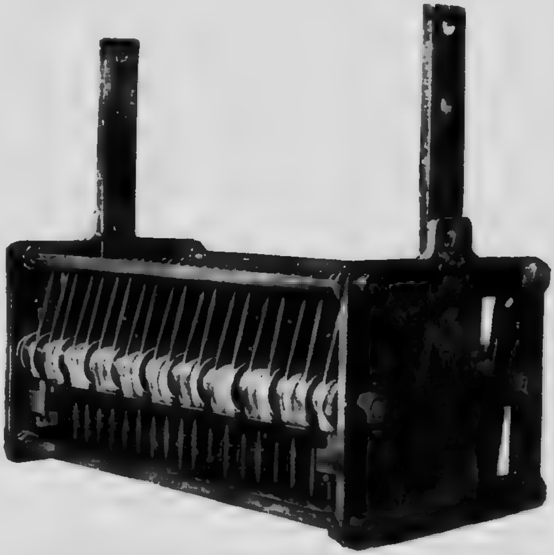


Fig. 758.—Westinghouse Resistance Frame for Rotor Circuits.

As already explained, the horse-power curve on the diagram is only applicable to the short-circuited rotor. For any of the other resistances the power must be calculated from the formula :

$$\text{H.P.} = \frac{\text{Torque} \times \text{R.P.M.} \times 2\pi}{33{,}000},$$

the torque being in pound-feet, as given in the diagram. It will be noticed that the periodicity is given on the diagram at 7,200 alternations, and the speed at 900 R.P.M. The former follows the American practice, in which each period is counted as two alternations, and the number of such alternations per minute instead of per second is specified. To reduce to ordinary English practice of specifying periods per second, the number given must be divided by 120. The speed of 900 R.P.M. is the synchronous speed, which the motor can only attain by running absolutely idle, absorbing no energy a condition never reached, as there is always friction of various kinds to waste some energy.

These motors have already been illustrated in Figs. 507 and 508 (Vol. I.), which show the stator and the complete motor. Fig. 758 shows one of the resistance frames used for the controller circuits. The conductors are in the form of grids, spaced well apart and clamped up between insulating blocks by long bolts secured to two massive end plates.

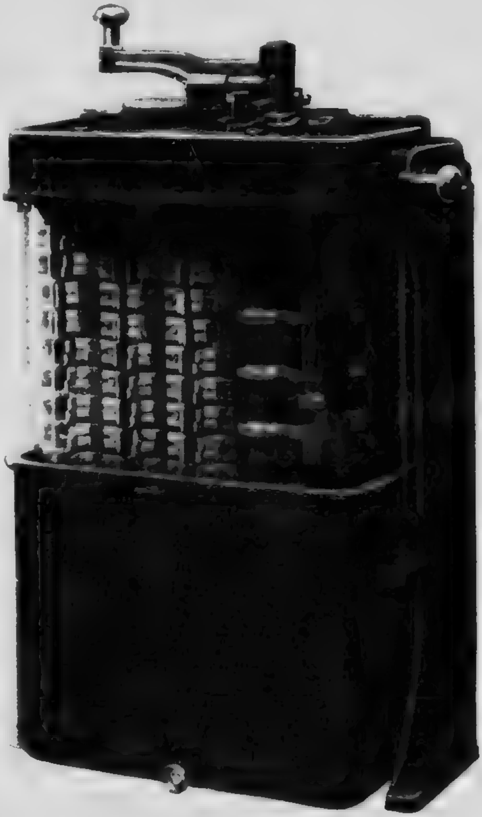
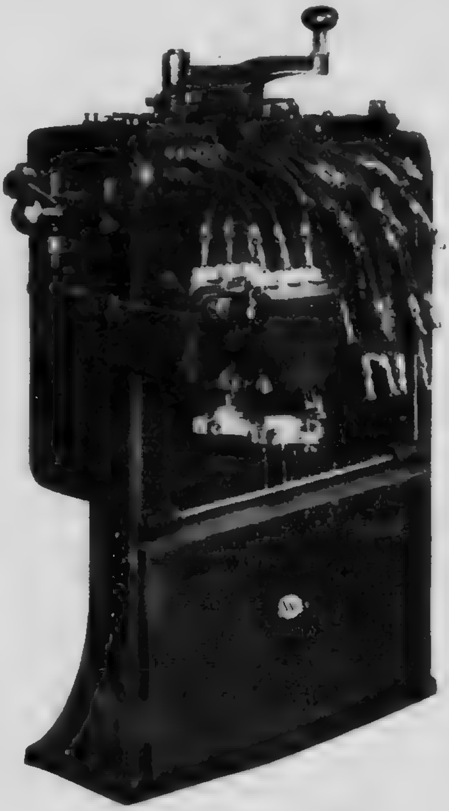


Fig. 759.—Dick, Kerr Controller with Oil Tank Lowered.

To illustrate the kind of controller, as distinct from the resistances, which is used for this work we select a recent "controller for heavy duty," manufactured by Messrs. Dick, Kerr and Co., Limited. The controller provides a reversing barrel for the stator circuits and a controlling barrel for the manipulation of resistances in the rotor circuits. As the rotor currents to be handled may be very heavy, though not of high voltage, the switch contacts are immersed in oil, a device which we have described elsewhere. The stator contacts are also immersed in oil, which for high voltages (3,000 volts) is in a compartment separate from that containing the oil for the rotor contacts.

A front view of the controller, with the oil tank lowered, is given in Fig. 759. The rotor contacts are in triple vertical rows on the left, and the stator contacts on the right, and with the oil tank down, all these contacts are quite accessible. A back view of the controller is given in Fig. 760. There are two bifurcating boxes, one for the incoming and the other for the outgoing stator cables, and on the right of the figure are the very numerous single conductor flexible leads for making the connections to the various sections of the three-phase resistance. The controller stands about 4 ft. high, and the oil tank can be readily raised and lowered, as its weight is counterbalanced by the metal slab W (Fig. 7[illegible]



[illegible]

The three contacts for a particular value of the three-phase resistance are arranged in a horizontal line and are manipulated simultaneously by a cam on the controlling shaft, this cam working against a spring. Details for a single line of contacts are given in Fig. 761. The fixed contacts are on vertical posts D, and the movable contacts C are attached to levers B working round spindles A attached to the fixed frame *a a*. The contacts C are pivoted at M on the levers, and work against springs when they are pressed on the fixed contacts D, thus giving the rubbing action which is so essential for the contacts of a switch mechanism of this kind. The three levers B are coupled together by pins G on the bar F, carrying a roller contact L at one end, which is pushed against the cam K by the spring H at the other end. This cam K is attached to the square shaft J, which is the controlling shaft, and there is, of course, a separate cam for each line of contacts, each cam being set to operate for a different position of the handle. The contour of the cam should be noted, for it is when the bulge at K presses on the roller L that the coupler I is forced to the left, and the contacts E C are closed. When this bulge has passed L the contacts are reopened by the pressure of the spring H. The cam is designed to give a rapid positive contact and a quick and decided action at breaking. There is, as usual, an automatic notching device, [illegible] ensures that the operator [illegible] move the handle forward one [illegible] at a time. In Fig. 750 the third and fourth rows of contacts are shown closed and the other contacts open.

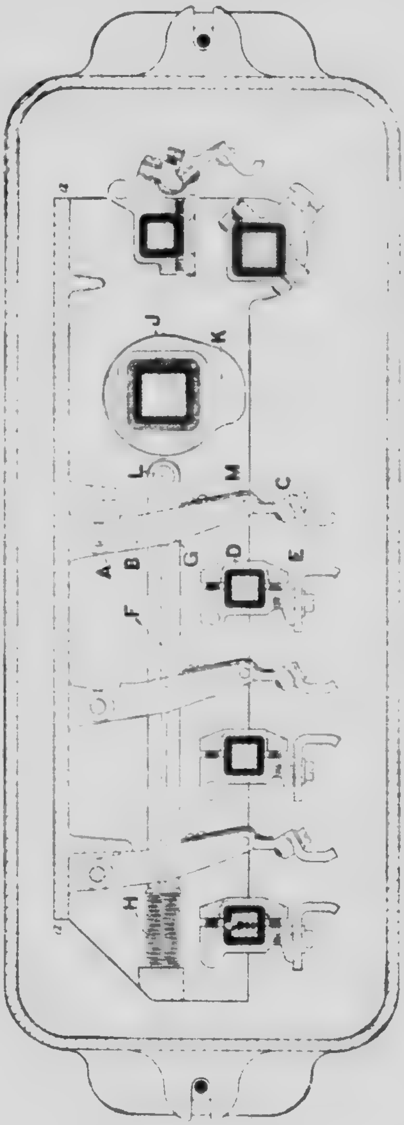


Fig. 751.—Line of Rotor Contacts [illegible] Kerr [illegible]

The reversing contacts for the stator circuit are shown at the right-hand end of Fig. 701. These are worked by cams on the reversing shaft, and the usual interlocking precautions are taken by which the reversing shaft can only be manipulated whilst the controlling shaft is in the off position with all the resistance in the rotor circuit. On the other hand, the controlling shaft is held locked until the stator circuit is closed for either forward or backward running.

Control by Varying Polarity of Stator. An obvious method of altering the speed of an induction motor is to change the number of poles of the rotating field set up by the stator if this can be accomplished without introducing practical difficulties or increasing unduly the cost of the machine. The squirrel-cage rotor will, of course, adapt itself to any number of poles in the stator. The method clearly requires the dividing of the stator windings into sections, the ends of which must be brought out to special switches or controllers by which the necessary changes can be made. Thus, for instance, if the windings of the stator are represented by the six coils, 1, 2, 3, 4, 5, 6 of Fig. 762, those coils can be formed as shown in a star winding to give, say, a six-pole rotating field. Let now the star point be opened out as shown in Fig. 763, so as to put in series the coils which were previously in parallel, but leaving the connections unchanged at A, B, and C, and partly unchanged at *a b*, *b c*, and *c a*. The effect will be to give a twelve-pole field rotating at half the speed. It should be noted that the supply leads in Fig. 763 are connected to the *a*, *b*, *c* terminals of the coils, and not, as in Fig. 762, to the A, B, C terminals; this ensures that the change made is as described, and leaves the direction of rotation unchanged, though the direction of the current is reversed in certain coils. The change alters the synchronous speed, and there will be the usual further variation due to variation of load (*see* Figs. 756 and 757).

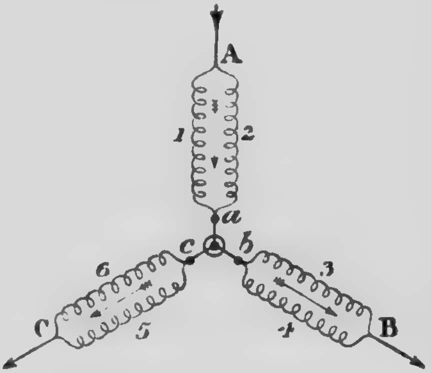


Fig. 762. Windings Connected for a Six-pole Field.

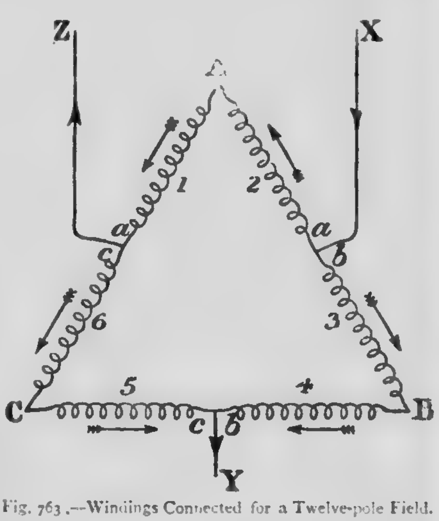


Fig. 763.—Windings Connected for a Twelve-pole Field.

Variable-speed polyphase motors on this principle have been built by the Oerlikon Company and by Messrs. Brown, Boveri and Co. In some locomotives built for the Simplon tunnel the connections for the stator circuits were so arranged that the motors could be run with 16, 12, 8, or 6 poles, with corresponding ranges of the synchronous speeds, at 25 periods, of 187·5, 250, 375, and 500 revolutions per minute. As the torque of such motors is inversely as the synchronous speed, the method has the advantage of giving the large torque at starting which is so important in traction work. Considerations of space will not permit us to give details of these motors, but the effect of the change of polarity on (i.) the speed, (ii.) the efficiency, and (iii.) the power-factor for different loads is given in Figs. 764 and 765, taken from Mr. Hobart's book on "Electric Motors." The motor experimented upon was a variable-pole railway motor giving 220 H.P. on a 25-cycle 550-volt circuit. The curves in Fig. 764 are for the twelve-pole stator connections, and those in Fig. 765 for the six-pole connections. In Fig. 764 not only is the speed lower than in Fig. 765, but also the power factor and the efficiency are substantially lower for the full-load rated output of 220 H.P.

Still more recently Mr. Creedy, by sectioning up the stator circuits and bringing out the terminals to a special phase-converter, has applied the principle of control by varying the polarity to large motors. At the 100-B.H.P. size he obtains nine running speeds, and even more in the larger sizes.

Control of Two Motors in Combination. In traction work with two motors available, methods were worked out some years since by which, with motors connected together, high efficiencies and running torques were attained at speeds much below the ordinary running speeds of either motor. Motors so connected are said to be coupled in "concatenation," "tandem," or "cascade." The last term is most generally used.

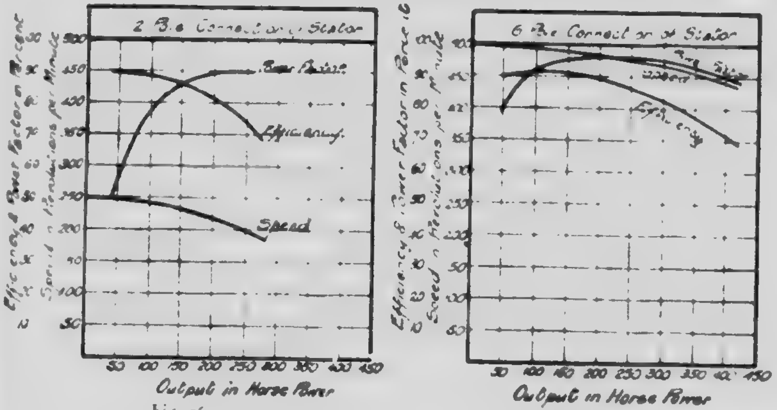


Fig. 764. Fig. 765.

Effect of Changing the Number of Poles on Speed Efficiency, Power Factor and Output.

The original method of connecting up two induction motors in "cascade" is shown diagrammatically in Fig. 766, in which S_1 S_1 S_1 represent the stator circuits and R_1 R_1 R_1 the rotor circuits of No. 1 motor, the latter being connected to the usual slip rings. The stator and rotor circuits of No. 2 motor are represented by S_2 S_2 S_2 and R_2 R_2 R_2 respectively; the necessary switches and fuses are not indicated in the diagram. For full speed the stators of both motors are connected in parallel to the mains, but for starting and for reduced speeds, as shown in the diagram, only the stator of No. 1 is joined directly to the supply mains. The stator of No. 2, it will

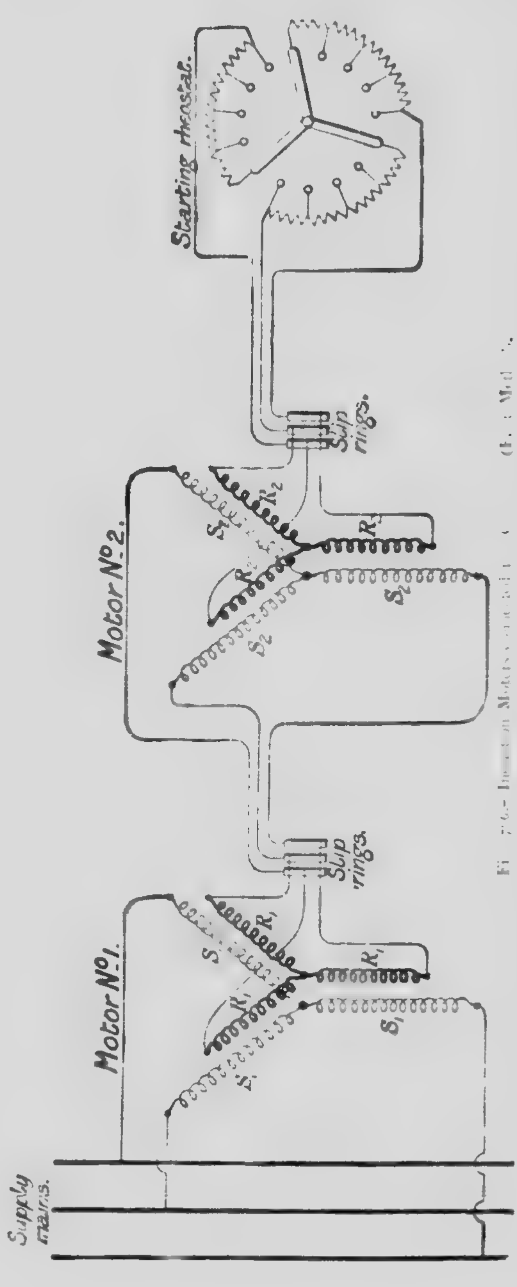
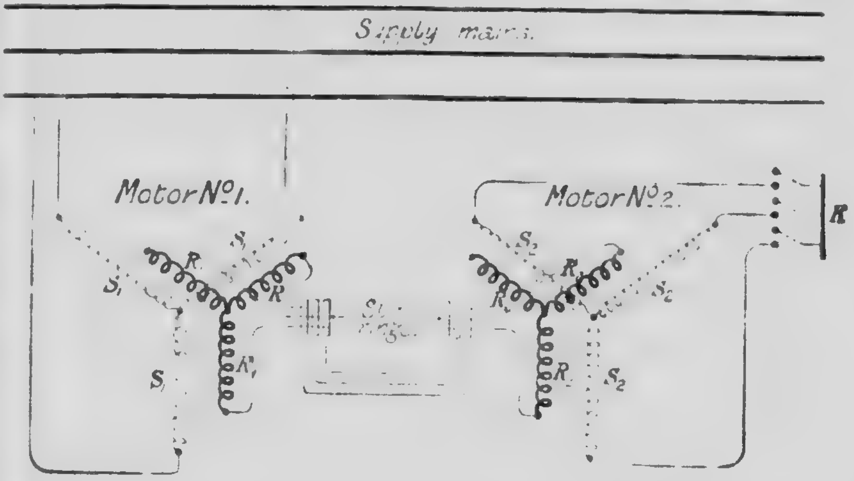


Fig. 76.—Induction Motors [illegible] ([illegible] Method).

be noticed, is connected to the slip rings of the rotor of No. 1, whilst the rotor of No. 2 is joined to the usual starting resistance. With this arrangement the frequency of the currents supplied to motor No. 2 depends upon the "slip" of the rotor of No. 1, and the motors, which if mechanically connected must run at the same speed, will run up to about half their normal full speed, at which speed, if they be similarly wound, the slip will be about one-half, and they will run at nearly the same efficiency as at full speed. An advantage is the flexibility of the method, and also that if the motors thus connected are driven at a speed between half and full speed, as, say, when the car is running down-hill, they will act as generators and return energy to the supply mains. The disadvantages are the complicated switching arrangements, and that, to obtain a sufficient E.M.F. in the rotor of No. 1 to feed the stator of No. 2, No. 1 rotor must be wound with fine wire, so as to have the requisite number of turns. This necessarily means a comparatively high resistance in this rotor, which is not advantageous when it is being run in the ordinary [illegible] In an early example of the application of this method the supply mains had a pressure of 3000 volts, and the rotor of No. 1 was wound to transmit 300 volts to the stator of No. 2; the power was 300 B.H.P. When running on the mains the efficiencies of No. 1 and No. 2 were 92·5 and 94 per cent. respectively, the difference being due principally to the high resistance of the stator of No. 1. The joint efficiency in cascade at about half speed was 77·5 per cent., which is much higher than could have been obtained with the two stators in series, so that each should take half pressure. Moreover, in the latter case the speed regulation would have been difficult and of little value.

A later method of coupling induction motors in "cascade" is shown in Fig. 727, in which the stators and rotors of the two motors are indicated in a similar manner to that used in Fig. 726. As before the stator of No. 1 is placed direct on the supply mains, and then the rotors of the two motors are placed in series with one another so that the rotor of No. 2 acts as a starting resistance, and something more, to the rotor of No. 1. The terminals of the stator of No. 2 are connected to K K K, by which they can either be short-circuited or through which external resistances can be introduced. The currents induced in the stator of No. 2 react upon its rotor, which is therefore not merely a simple resistance in the circuit of R₁ R₁ R₁. By this method of connection the two machines can be made similar to one another, and the necessity for and disadvantages of winding R₁ R₁ R₁ with a large resistance will disappear.



[illegible]

For traction and many other purposes it is desirable that the two machines in "cascade" should run at the same speed, and in the [illegible] they can be mechanically geared together. If the second method of connection referred to above be adopted, the machines can be placed on the same bed-plate and the rotors built on the same shaft; no slip rings will then be required, since the necessary connections can be passed along the shaft. In this case the set becomes an alternate-current motor with starting and speed-controlling resistances inserted in the circuit of the stator of No. 2. Further simplifications suggested by Dr. S. P. Thompson were to wind the two stators on one core and the two rotors on another.

Cascade Motors.—In 1907, Mr. F. J. Hunt, in a paper read before the Institution of Electrical Engineers,* described a remarkable development, in which not only was a single core used for the stator and a single core for the rotor, but also a single winding on each gave all the conditions necessary to take advantage of the "cascade" principle. To understand this achievement it must be remembered that the currents supplied to No. 2 machine by either method described above are of lower frequency than that of the supply currents. If, therefore, the number of poles for which No. 2 is wound be the same as No. 1, the synchronous speed of No. 2 for these currents will be correspondingly lower. Another way of putting this result is to say that the speed in each case is that of a synchronous motor with a greater number of poles supplied with currents of the "line" frequency. Thus if running at half-speed with a six-pole winding this speed may be referred to as that of a twelve-pole motor of the original frequency.

In Hunt's cascade motor the rotor is so wound that its induced currents not only produce a field of the same number of poles (p_1) as that of the stator, but also a field with fewer poles (p_2), say one-half or two-thirds. This field, of course, rotates with a lower angular velocity than that of the other field, and in the case of an eight-pole four-pole combination, for instance, would not react upon the circuits of an eight-pole stator wound in the ordinary manner. Hunt, however, modifies the winding of the stator so that while providing the usual eight-pole winding for the supply currents, a four-pole closed circuit winding is also provided in which the four-pole field of the rotor produces induced currents, and which acts as a rotor squirrel-cage winding towards the four-pole currents in the rotor.

It is only possible, with the space at our disposal, to indicate very generally how these results may be attained by suitable modifications of the windings of the stator and rotor of an ordinary three-phase induction motor. As regards the stator winding, the first step is to have in each phase two paths in parallel, as shown in Fig. 768, between the terminal and the neutral point of a star-connected winding. It follows that points A, A$_1$ and B, B$_1$, equidistant in any phase from the terminal, will be at the same potential at every instant, as regards the supply currents received from the terminal, and may therefore be connected either by a short cirnt or through an external resistance without interfering in any way with these supply currents. These currents will in any given case set up in the stator a revolving field of definite polarity, say eight-pole. Conversely, if an eight-pole revolving field were to sweep over these conductors the induced E.M.F.s, whilst causing alternating P.D.s at the terminals T_1 T_2 T_3, which would supply currents to any outer circuits connected thereto, would not give rise to any currents in the cross connections referred to, the ends of each of which would always be at the same potential for every position of the revolving field. For a four-pole revolving field, however, if the spacing of the coils of the two parallel circuits has been properly arranged, the connected points may be in opposite phase at every instant. This is obvious when it is remembered that conductors which are 360 electrical degrees apart in an eight-pole field are only 180 electrical degrees apart in a four-pole field. In Fig. 768 the exterior arrow-heads in each of the phases show the induced currents due to a four-pole field, whilst the interior arrows show the direction of the supply currents producing the eight-pole field.

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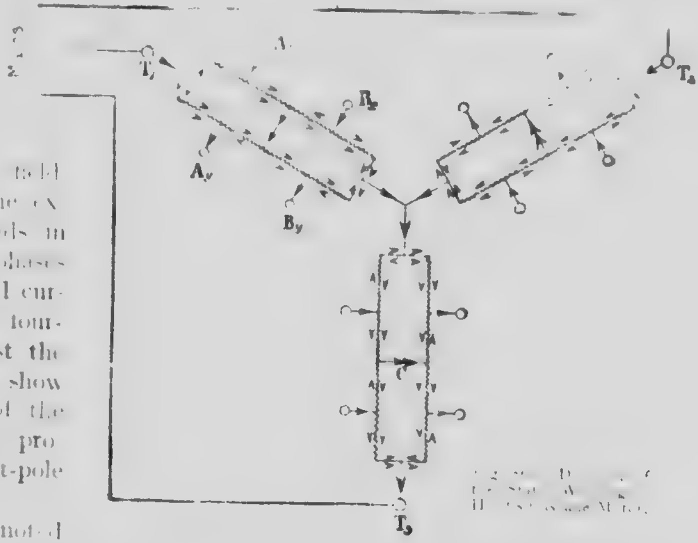
* *Journal of the Institution of Electrical Engineers*, Vol. XXXIX., page 648 (1907).



[illegible]

It may be noted here that the frequency of the currents in the main circuit coming from the terminal T_1 is the full frequency of the supply leads, whilst the frequency of the induced currents in the other circuits is that determined by the slip of the rotor relatively to the revolving field of the stator.

With the rotor the conditions are different, for both windings are to carry currents of the same frequency, and there are to be no external connections.

The same conductors preferably should supply all the necessary paths, that is, taking the case considered above, the paths for the eight-pole and the four-pole circuits, though, of course, it would be possible to have two entirely independent windings, and, as a matter of fact, such windings were adopted by Mr. Lydall in an earlier application of the "cascade" principle to a single motor. The practical objections are that it leads to unnecessarily high losses in the two sets of windings and high magnetic leakage caused by the greater depth of the slots.

To explain how the two independent windings of Lydall have been, as it were, fused together in a single winding by Hunt, we shall follow as briefly as possible the latter's exposition of his method given in a subsequent paper read before the Institution of Electrical Engineers early in 1914. For simplicity a four-pole two-pole combination is taken instead of an eight pole four-pole one as referred to above.

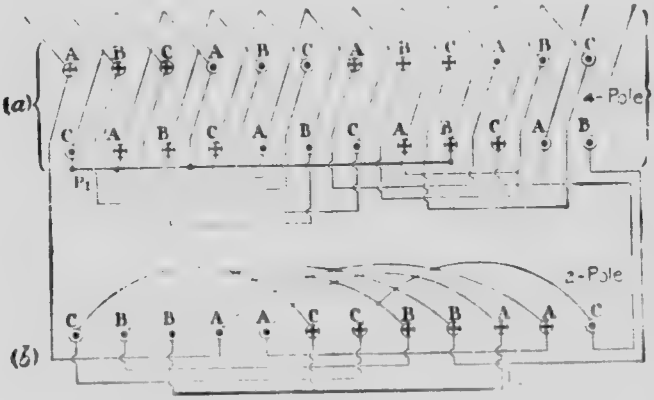


Fig. 769.—Diagram of the Rotor Winding in Hunt's Cascade Motor.

In Fig. 769 there is first set out an arrangement of thirty-six conductors in twelve slots, so connected as to give in the upper two rows a four-pole field and in the third or lowest row a two-pole field, that is, assuming the conductors carry the currents indicated. The usual conventions of + for a retreating and · for an advancing current are used. The three conductors in the same vertical line are supposed to be in the same slot, and the diagram is a developed one in which the last slot on the right is followed immediately by the first slot on the left. The currents are three-phase the phases being indicated by the usual letters A, B, and C. If these circuits are traced out it will be found that all the bars of each phase are in series between the neutral points P_1 and P_2, between which the three phases are in parallel. In the second diagram (Fig. 770) the combined winding is shown with the omission of the redundant bars, which, lying in the same slot, carry equal and opposite currents on the same phase. Thus slot 2, Fig. 769, shows two B-phase conductors, one carrying a + and the other a · current

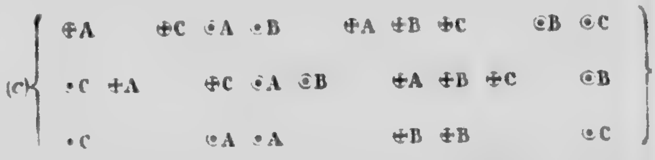


Fig. 770.—Simplified Diagram of the Rotor Winding, with redundant Bars omitted

These two currents would obviously cancel one another as regards magnetic effect, and therefore the only effective current is the A-phase current. It will be found on comparing the two figures that twelve conductors are thus omitted, reducing the thirty-six conductors of Fig. 769 to twenty-four. No connections are shown in Fig. 770, which only means that if by proper connections the currents shown can be passed through the conductors which remain the magnetic effect will be the same as in Fig. 770. Six of the slots now carry one conductor each and the other six carry three each. Further, in each of these latter two of the conductors carry currents in the same phase, and the current in the third bar differs in phase from the others by 60 degrees.

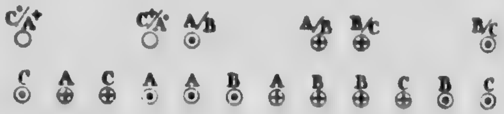


Fig. 771.—Rotor Winding Diagram further simplified

A further simplification appears in Fig. 771, in which two of the three conductors in the six slots just referred to are replaced by a single conductor, carrying the equal out-of-phase currents of the suppressed conductor. Assuming all the phase currents to be equal, this combined current will be 1·73 times the current in each of the two replaced currents, its phase being halfway between. The conductors carrying the combined currents are shown in the top row, in which the method of indicating the combination will be readily followed.

It is now possible to work out a plan of connections which will fulfil the conditions. Such a plan is shown in Fig. 772 in skeleton, and in Fig. 773 with the conductors in their proper positions in the slots and with the actual connectors shown. The connections give a star-mesh connection as drawn out in Fig. 774, the neutral point of the star being given by the conductor F in Figs. 772 and 773. An analysis of the induced E.M.F.s in the various circuits show that these, taken round the mesh, are balanced, and that no currents can circulate except by way of the star windings. There are thus three circuits in which currents circulate, namely those indicated by the three inner triangles of Fig. 774, and with the induced currents flowing in these circuits the four-pole and the two-pole fields of Fig. 769 are [illegible]

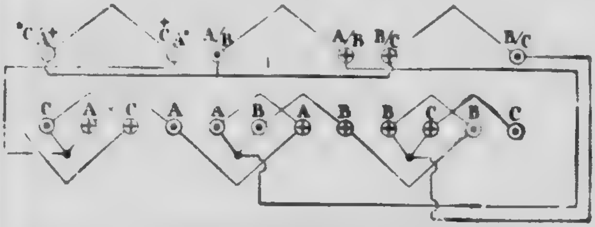


Fig. 772.—Connection Diagram of the Simplified Rotor Winding of Fig. 771

The working out of the full details of the windings of the stator and of the rotor in a given case would demand more space than we can spare, but the reader who wishes to carry the matter further may consult a lucid article * contributed to *The Electrician* by Mr. F. M. Denton.

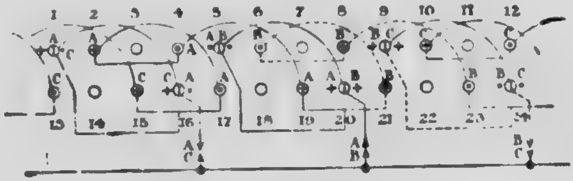


Fig. [illegible]
[illegible] Hunt's Cascade Motor.

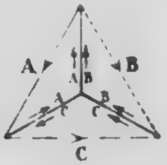


Fig. 774.

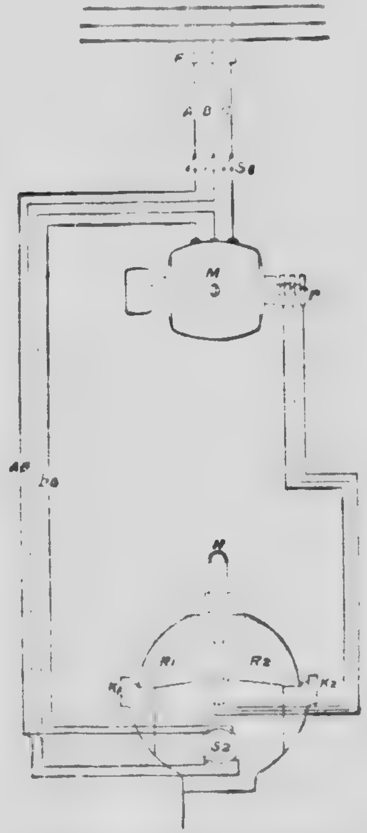


Fig. [illegible] Reversing [illegible]

Reversing.—To reverse the direction of rotation of a polyphase motor it is only necessary electrically to change some of the connections, so as to change the direction of rotation of the revolving field of the stator. This is accomplished in a diphase motor if the connections of one only of the phases be reversed, leaving the other unchanged. Similarly, in a triphase motor, if the connections of the mains to two of the terminals are reversed, the stator field and therefore the rotor, will revolve in the opposite direction. So far, therefore, as the stator circuits are concerned, in each of these cases a simple double-pole reversing switch on two of the leads is all that is necessary.

As regards the rotor circuits, it must be remembered, of course, that before the direction of motion of the rotor can be reversed it must stop dead and then start again in the opposite direction. The usual precautions necessary for starting from rest must therefore be observed. For instance, if resistance in the rotor circuits is the starting device employed, then the reversing gear should introduce resistance into the circuits as the rotor slows down, and remove it as the speed again increases.

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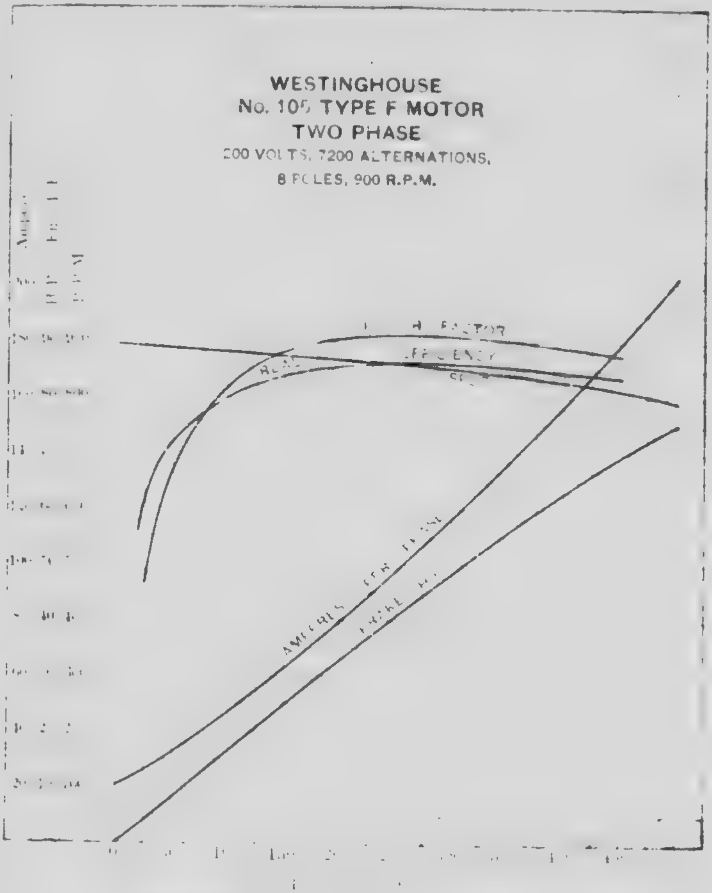
* *The Electrician*, Vol. LXXII., pages 524 and 871 (1914).

The necessary reversing connections, under such conditions, for both the stator and rotor circuits of a triphase motor are given diagrammatically in Fig. 775. Two of the leads A and B coming from the supply mains through the fuses F and the main switch S_1, instead of being directly connected to the motor M, are carried to the reversing switch S_2, whence the current is brought



F[illegible] 776.—[illegible] Motor.

[illegible] to the motor by the leads *a* and *b*. In one position of S_2 A is joined to *a* and B to *b*, and in the other position these connections are reversed. The movement of the handle H which actuates these contacts also lowers [illegible] other of the sets of triple blades [illegible] or K_2 into the liquid contained in the semicircular vessel, which acts as a variable resistance depending [illegible] the amount of the immersion of the plates, which in its turns depends on the position of the handle H. The blades of R_1 and R_2 are joined to the slip rings *r r r* of the rotor in the usual way by leads, independent of A, B, and C, and there are short-circuiting blocks K_1 and K_2 on each side of the switch. The modifications required in applying the principle to a metal starting resistance will be readily understood without further explanation.

Experimental Tests.—The behaviour of a well-designed modern induction motor has already been set forth in detail on page 697 (*see* Fig. 700) in connection with the full description of the Bruce Peebles standard induction motors. Curves plotted to a torque base line of a standard Westinghouse motor are given in Fig. 776, which has reference to the same Westinghouse motor which has been dealt with in Fig. 757. The motor is nominally of 50 B.H.P., but most of the curves are carried up to 75 B.H.P., which is a 50 per cent. overload. The various quantities are plotted vertically against the torque, which is plotted horizontally, as in the preceding diagram. This is justified by the fact that for a given torque the current and the power factor are constant and are independent of the speed. The speed plotted on the diagram is the maximum speed attainable with the corresponding torque, and with the rotor short-circuited. It will be noticed that the power factor, which is 50 per cent. at about one-tenth load, rises rapidly with the load, and reaches 90 per cent. at a little over half-load. It remains over 90 per cent. from this point until up to full load, and beyond to about 15 per cent. overload, and at 40 per cent. overload it is still as high

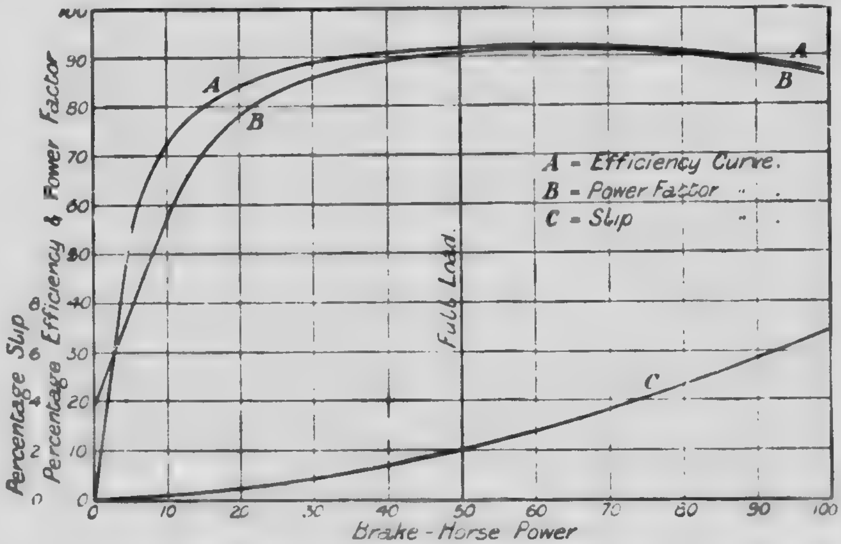


Fig. 777.—Working Curves of a 50-H.P. Induction Motor.

as 87·5 per cent. The efficiency for a fair range of load within ordinary working limits is over 85 per cent., but sinks to below 60 per cent. at very light loads. The current required is nearly proportional to the torque, but is somewhat higher than proportionality both at very light and very heavy loads. A tangent from the origin touches the curve very close to the full-load point, and lies quite close to the curve for a considerable distance. The disadvantage of using the torque as the horizontal ordinate is that, because of the varying speed, it does not represent the power the motor is giving out under the different conditions of the experiments.

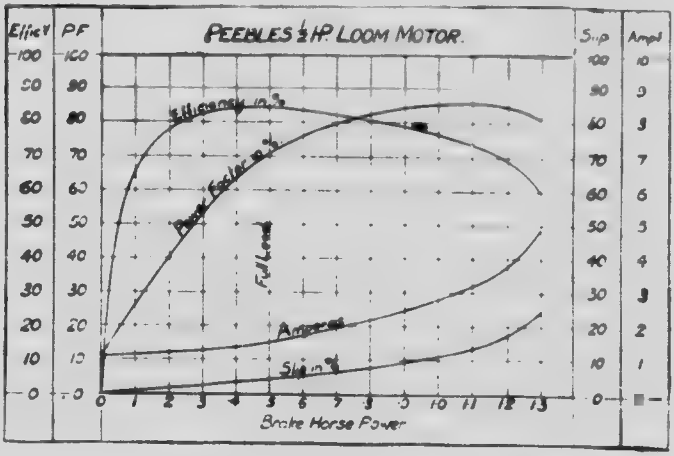


Fig. 778.—Working Curves of a ½-B.H.P. Bruce Peebles Motor

In Figs. 777 to 779 are plotted the results of tests on typical polyphase induction motors. In these diagrams the horizontal ordinates are the actual power (in B.H.P.) developed by the motor, and they show the relations between this power and the efficiency, the power factor, and the slip respectively, the last-named being plotted for clearness in Figs. 777 and 779 on a scale two times that of the other two. Fig. 777 illustrates the behaviour of a [illegible] H.P. motor from no load up to a 100 per cent. overload. At full load the efficiency is [illegible]2 per cent., and the power factor nearly 91 per cent., and these quantities change very little for a considerable range of load and overload. The slip on the other hand, which is only 2 per cent. at full load, rises [illegible] to 6·75 per cent. with the heavy overload of 100 per cent., but even at this value the actual change of speed is not very great.

Fig. 778 illustrates the behaviour of a small Bruce Peebles ½-B.H.P. induction motor specially designed for loom driving. In these small motors it is impossible to obtain the high efficiencies and power factors attainable in larger motors, and it will be noted that the full load efficiency in Fig. 778 is only about 85 per cent., the corresponding power factor being 70 per cent., and the slip about 4 per cent. The curves extend to a load of 1·3 B.H.P., which is an overload of 100 per cent.; it is interesting to note that the motor will run at such a heavy overload but of course this load must not be kept on for a long time.

For contrast, Fig. 770 gives the corresponding curves of a very small polyphase induction motor whose full load is one-sixth of a horse-power, or about 90 foot-lbs. per second. Here the efficiency at full load is only 61 per cent., and the power factor is as low as 54 per cent. Both these, and especially the latter, rise to much higher values as the load is increased, and with an overload of 150 per cent. the power factor is over 75 per cent. The slip reaches, within the limits of the diagram, the high value of over 14 per cent., but at full load is as low as 2·7 per cent., showing that up to this point the motor, like the 50-H.P. machine, is nearly synchronous.

The Rating of Polyphase Induction Motors.—The rating—that is, the actual B.H.P. output of a polyphase induction motor—is governed

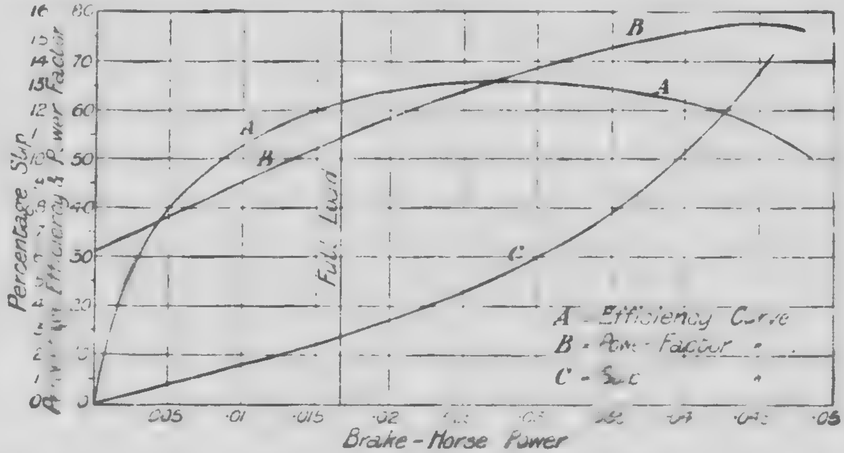


Fig. 770.—[illegible] a Very Small [illegible]

primarily as [illegible] the case [illegible] the continuous current motor [illegible] the speed and [illegible] permissible temperature rise under the conditions which the motor has to satisfy in working. [illegible] has been considered in connection with [illegible] Section [illegible] and [illegible] considerations [illegible] motors. [illegible] after a [illegible] well understood that [illegible] work intermittently and [illegible] might be safely taken [illegible] on the Fahrenheit scale [illegible] considerable [illegible] this excess in [illegible] is often [illegible] the motor [illegible]

[illegible] with different parts of the machine at the end of the trial run, the [illegible] temperature being calculated by taking the difference between the observed temperature of the room and that of the machine so ascertained.

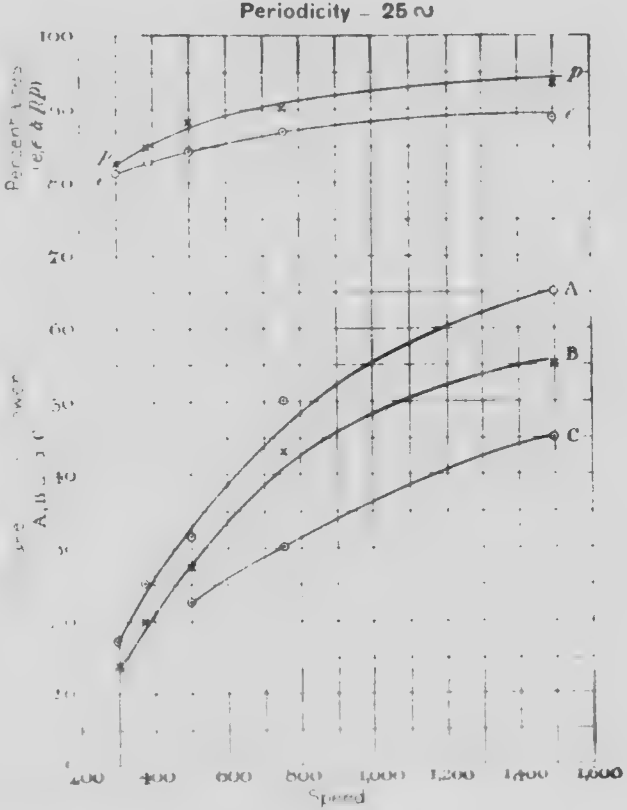
The new factor in connection with polyphase induction motors is that the polarity—that is, the number of poles given by the winding—and the frequency of the supply current, fix the speed within narrow limits, and therefore indirectly become factors in the rating. Also the voltage of the supply circuit must be taken into account, because much higher voltages can be used with A.C. than with C.C. motors. Now with a given carcass on account of the much heavier insulation required for high voltages the "space-factor" or the fraction of the winding space occupied by the copper becomes very low, and thus the output is lower for a given carcass than it is for low voltages, because of the [illegible] resistance and the consequent greater development of [illegible] heat.

These considerations will probably become [illegible] taken from the case of the D 15 [illegible] Brown Boveri [illegible] induction motor, already described [illegible] of a [illegible] ~ [illegible] moderate voltage this size is wound, with [illegible] number of poles from four to sixteen, and therefore for a synchronous speed of from 1,5[illegible] to 375 R.P.M. The actual speed will be [illegible] by the amount of the slip, which varies from 3¼ per cent. [illegible] to 5½ [illegible] for the lowest. Within this [illegible] the power [illegible] low-voltage supply from 75 to [illegible] B.H.P., which shows that the [illegible] to speed is not a constant quantity, [illegible] ratio is proportional to the torque.

The influence of voltage is still more interesting, since [illegible] above its increase tends to lower the rating of the machine [illegible] strikingly shown in the curves plotted in Fig. 78[illegible], in which curve [illegible] voltages between 110 and 600, curve B for 625 to 1,100 volts, curve C for 1,125 to 3,500 volts, the actual curves being for about the m[illegible] voltage in each case.

The influence of lowered periodicity is to decrease the output at [illegible] speeds and to increase it at the lower. This can be noted by [illegible] the curves in [illegible] (in which the periodicity is [illegible]) with the [illegible] complete the data the power [illegible] full [illegible] and the efficiency at full load in the [illegible]

Polyphase v. Continuous-current Motors.—We may [illegible] this section with a brief comparison of the [illegible]



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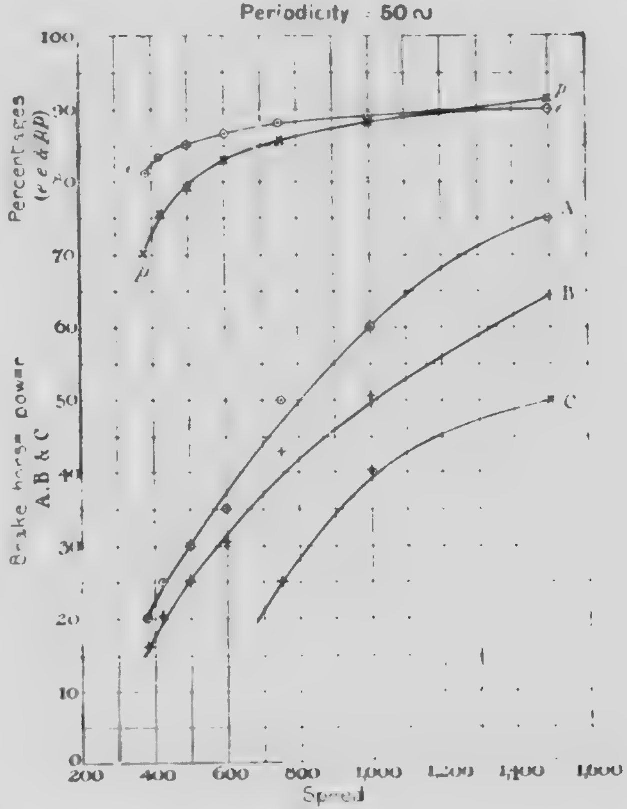

Fig. 78b.

. . . the Influence of (i) Voltage and (ii) Periodicity on the Rated Output of Induction Motors commutator with all its troubles, and, in the case of squirrel-cage rotors, in the absence of all rubbing contacts other than the unavoidable ones at the bearings. Then the polyphase motors have a big starting torque, and can start against a full load; whilst as regards speed, they are practically self-regulating, the percentage change in the slip, as an inspection of the curves given above will prove, being practically negligible for a wide range of load. They are also as light as continuous-current motors of the same output, and more compact, and in addition can stand big overloads at nearly full efficiency for short periods of time.

Power Factor.—The one great disadvantage which polyphase motors have is in the existence of the power factor. This necessitates the supply of a larger current at the standard pressure than would be required by a continuous-current motor for the same amount of power. If the power factor be low this extra current will either cause a greater loss of power in the distributing conductors, or heavier conductors, involving a greater capital expenditure, must be put down to carry it. In either case there is an additional loss, which, even with a fairly high power factor, may be serious. Thus, suppose a certain required amount of power can be supplied to a continuous-current motor by a current of 80 amperes at a certain voltage, and it is proposed to replace the motor by a polyphase one wound for the same R.M.S. voltage, and which at the load required has a power factor of 80 per cent.; then a current of 100 amperes must be supplied to the new motor in order that its mechanical output may be the same, assuming that the efficiencies of the two motors are equal, a condition which can be attained in practice. Now, if the distributing leads are the same in the two cases the amounts of heat generated in them by the two currents will be as [illegible], or as 16 to 25, an increase of 56 per cent. As far as the heating of the leads is concerned, it is as if an independent current of 60 amperes (giving a heating effect of 3,600) had to be transmitted by the same leads instead of simply 20 amperes extra. This is because the heating effect goes as the *square* of the current, and not as the current only.

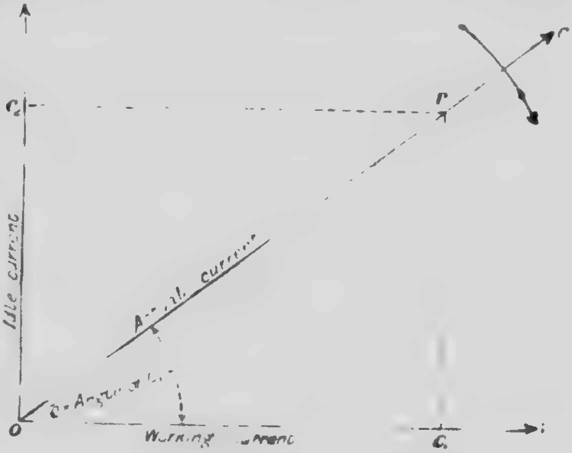

Fig. 78a.—"Idle" and "Working" Currents.

The point may be examined instructively by means of a vector diagram. In Fig. 782 let O V be the voltage supplied to the motor; then with a power factor of 80 per cent. (0·8) the current will be represented in the correct phase relation by a vector drawn along O C, the cosine of the angle C O V being 0·8. Let O P represent this current in magnitude, then it may be resolved into two currents in quadrature (i.e. differing a quarter period in phase), one O c_1 in the direction O V, and the other O c_2 at right angles to O V. If O P be 100 amperes, O c_1 will be 80 amperes and O c_2 will be 60 amperes. The two currents O c_1 and O c_2 will produce the same effects as the current O P with regard to both power and heating of conductors. As regards power, the current O c_1 being in step with the pressure O V, we shall have the

$$\text{Power} = \text{O V} \times \text{O}c_1 = \text{O V} \times \text{O P} \times \text{Cos}\,\phi,$$

the latter being the proper expression for the power given to the motor. With regard to the current O c_2 we have the

$$\text{Power} = \text{O V} \times \text{O}c_2 \times \text{Cos}\,90^\circ = 0.$$

This current, therefore, contributes nothing to the power, and is therefore often referred to as the *idle current*, whilst O c_1 is known as the *working current*. That these two currents are equivalent in heating effect to O P is evident if we remember that

$$\text{O}c_1^2 + \text{O}c_2^2 = \text{O P}^2$$

and therefore $(\text{O}c_1^2 \times \text{R}) + (\text{O}c_2^2 \times \text{R}) = (\text{O P}^2 \times \text{R}),$

where R is the resistance of the conductor. Now in the last equation the terms on the left represent the watts wasted in heat by the currents O c_1 and O c_2, and the term on the right the watts wasted in heat by the current O P; the proposition, therefore, is proved.

Even with a power factor of 90 per cent., which enables an alternate current of 100 amperes to do as much work as a continuous current of 90 amperes, the idle current is as high as 36 amperes, and the extra energy wasted in the same leads would be 23·5 per cent. As the power factor approaches unity this extra energy wasted in heating the leads still further diminishes, and eventually vanishes, when the current falls into step with the pressure, and the power factor becomes 1. The importance of a high power factor for motor work is therefore very apparent.

Another objection urged against alternate-current motors is the large and lagging starting current required, a point to which allusion has been made elsewhere (*see* page 726). We have shown how these starting currents can be diminished with polyphase induction motors, and the point will be referred to again when dealing with monophase motors. It will be remembered that one of the evils consequent on large starting currents is their possible interference with the voltage regulation of the distributing system.

Another point in which the polyphase induction motor does not compare well with continuous-current motors is the comparative inflexibility of its speed ranges. For constant speed work the polyphase motor is excellent, but for conditions of service in which wide variations of speed are necessary, it is at a distinct disadvantage. Some of the methods designed to overcome this disadvantage have been dealt with in the preceding pages.

Finally, it may be said that the polyphase motor is better adapted for *high speeds* than for low speeds, and that its advantages increase as the periodicity of the supply currents falls, so that wherever such motors are largely used it should be with *low periodicity*.

IV. FURTHER NOTES ON THE ELEMENTARY THEORY OF INDUCTION MOTORS

The elementary theory of induction motors from the physical point of view has been dealt with with some fullness in Vol. I. (*see* pages 610 *et seq.*), in which the principles of electrical science were under consideration. Further, as a machine for converting electrical into mechanical energy the induction motor has certain points of theory in common with continuous-current motors, which have been touched upon in Vol. I. (pages 601 *et seq.*) and in the earlier sections in this volume (*see* pages [illegible]1 *et seq.*). Still further in the preceding sections of this chapter matters in which theoretical questions have arisen have received attention. The present section must be regarded as somewhat supplementary to all these, and intended only to bring out a few simple points and methods of treatment which are of importance.

The full mathematical theory of the induction motor is very complicated, and has given rise to a voluminous collection of mathematical literature chiefly because the methods of approximation by making assumptions which neglect the influence of certain small factors are almost infinite in their variety. Each such assumption simplifies the theory, and by the skilful use of vector diagrams, which in themselves often involve unspecified assumptions, very pretty geometrical demonstrations can be developed, some of which may be regarded as mere intellectual exercises. There are, however, other demonstrations, which are of real practical value, both from the point of view of the designer in predetermining the performance of a motor not yet constructed, and from the point of view of the user who, by means of a few simple tests, can obtain data from which the performance of an actual machine under various conditions can be predicted almost to any degree of approximation.

The Circle Diagram. Many of these, where practically applied, depend upon what is known as the "circle diagram," which was first put forward by Alexander Heyland in 1894, and described by him in his paper '*Eine Methode zu Experimentellen Untersuchungen an Induktions-motoren,*' of that date. Since then this diagram, the value of which has been generally recognised, has been modified and elaborated by many writers

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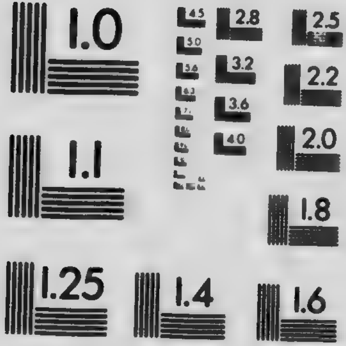

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without disturbing, however, the underlying simplicity of its fundamental parts.

The diagram can be drawn either from experimental data or from data ascertained from the particulars of the design and construction of the motor. It is a *clock-* or *vector-diagram*, and the principles on which such diagrams are based have been explained in Vol. I. at page 542. Each principal line of the diagram represents a complete sine curve, the length of the line corresponding to the semi-amplitude of the curve, or more usually to the R.M.S. value of the vector and the angular position of the line, giving its phase relations with the curves represented by other lines.

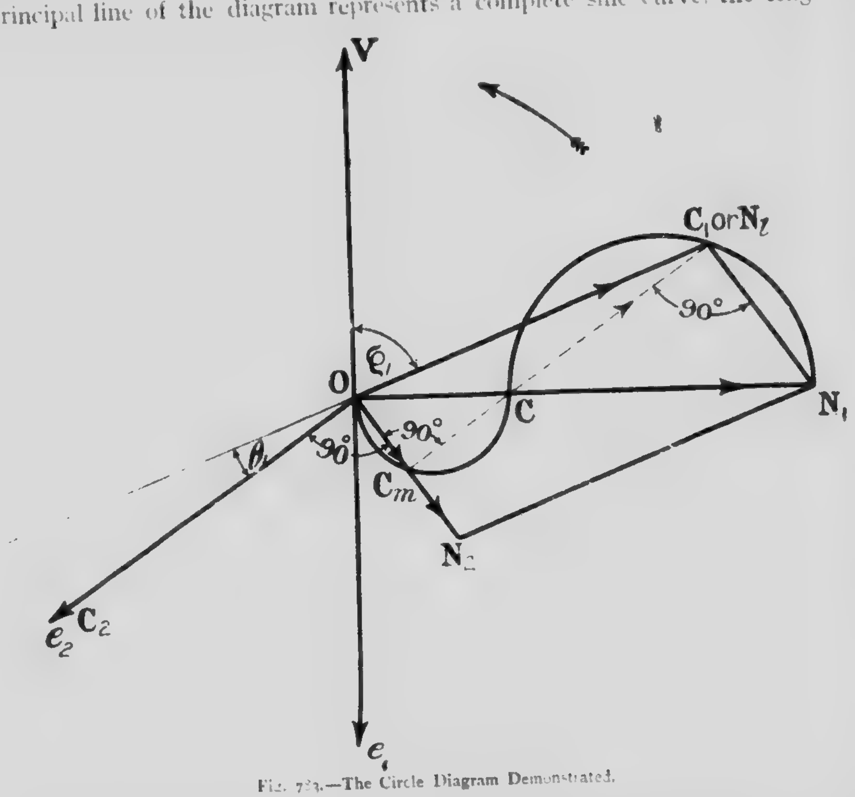

Fig. 723.—The Circle Diagram Demonstrated.

To draw the "circle diagram" for an induction motor from experimental data two experiments have to be made on the completed motor. For the first, the motor is run quite light, that is with its shaft unloaded, under full-line voltage, and readings are taken of the voltage, the "no-load" current (c_0) and the no-load watts (w_0) supplied to the stator or primary and absorbed by the motor. From this, known as the "no-load" test, are found :—

The "no load" power factor $= \dfrac{\text{W}}{\text{Line volts} \times \text{C} \times \sqrt{3}} = \text{Cos}\,\phi.$

The "no load" lag $= \phi$.

The second test is known as the "stand-still" or "locked" test: in it the rotor is jammed so as to be prevented from rotating, and the full line voltage being applied to the stator, the volts, "stand-still" amperes [illegible] and the "stand-still" watts (W) are again measured, and there are thus found in addition:—

The "stand-still" power-factor $= \dfrac{\text{W}}{\text{Line volts} \times \text{C} \times \sqrt{3}} = \text{Cos}\,\phi.$

For large machines it may not be safe to apply the full line voltage with the rotor locked, and in these cases such a lower voltage is applied as will send the normal full-load current through the primary, and this current is measured. The assumption is made that had the full voltage been applied the current would have been correspondingly greater, and that the power factor would have been the same. The $\sqrt{3}$ is introduced in the above denominators because it is assumed that C is the line current in one phase only.

Dealing first generally with an induction motor under ordinary conditions of load and with a short-circuited rotor, let O V (Fig. 783) represent $\dfrac{1}{\sqrt{3}}$ of the constant R.M.S. voltage V applied at the terminals of the stator; in other words, the voltage per limb of the stator assumed to be star-wound. If we neglect the fall of potential $C_1 R_1$* due to the resistance R_1 of each limb of the stator, a quantity which in modern machines is quite small compared with V, the back electromotive force e in each limb of the stator circuit will be represented by O e_1, which is directly opposite to and equal in magnitude to V. This back electromotive force e_1 is due to the time variation $\left(\dfrac{d N_1}{d t}\right)$† of the stator flux, with which it is in lagging quadrature, and therefore this flux is represented by a vector O N_1 at right angles to O e_1, and leading in phase on O e_1 by 90°.‡

Draw next the vector O C_1 lagging in phase behind O V by an angle of lag ϕ_1, and representing any current C_1 on the stator circuit. The current C_2 in the rotor circuit, it being assumed that the number of turns of the rotor conductors is equal to that of the stator conductors,* will be represented by the vector OC_2, nearly equal in magnitude and nearly opposite in direction to OC_1, but leading by a small angle θ on this reversed direction. We shall assume that this current C_2 is in phase with the inductive E.M.F. (e_2), which gives rise to it, an assumption which treats the reactance, and therefore the inductance, of the short-circuited rotor as negligible. This inductive E.M.F. is set up by a portion only of the main flux X_1, since, owing to the existence of the air gap and the separation in space of the stator and rotor conductors, the whole of the flux due to the M.M.F.s does not link round the rotor conductors. The flux X_1, for our purpose, may be regarded as divided into two parts, one X_2 which links round the rotor conductors and the other X_l, a *leakage* flux, which lies in paths passing between the two sets of conductors. Now the flux X_2, as explained above, must lead 90° in phase on Oc_2, and therefore may be represented by a vector OX_2 having this position and due to a component OC_m of the stator current OC_1, which may be described as the "rotor magnetising current." The other and corresponding component ($C_m C_1$) of the total stator current OC_1 will be equal and opposite to OC_2. Similarly the other component X_l, which with OX_2 makes up the total flux OX_1, may be represented by a vector OX_l in phase with and due to the stator current OC_1, the two components OX_2 and OX_l, when combined, giving the total flux OX_1. Thus Fig. 783 may be regarded as giving the phase relations of voltages, currents, and fluxes with the relative magnitudes of the components of the two latter on the assumption that the resistance of the stator circuit and the inductance of the rotor circuit are practically negligible.

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* In what follows the subscript numbers 1 and 2 will usually refer to the stator and rotor [illegible]ively; thus C_1, R_1, e_1, etc., will mean current, resistance and E.M.F., etc., in the stator [illegible] C_2, R_2, e_2, etc., the corresponding quantities in the rotor.

† See page 542, Vol. I.

‡ In the following diagrams the direction of the rotation of the vectors is counter clockwise not clockwise as in Vol. I. (pages 540 *et seq.*): since the earlier figures were published [illegible] International Electro-Technical Commission has adopted counter-clockwise as the standard [illegible]tion. It is also to be understood that the different quantities, *volts*, *amperes*, *flux*, etc [illegible] drawn each to its appropriate [illegible], though these [illegible] may [illegible] adjusted that the [illegible] vector may represent different quantities, provided always that these quantities are [illegible] [illegible]

It remains to prove that the point C_1 lies on a circle (or semicircle). It will be noticed that the current vectors are OC_1, the stator current, OC_2 the rotor current; OC_1 has two components, OC_m the rotor magnetising current and $C_m C_1$, equal and opposite to OC_2. Of these the two latter in the stator combine to give the actual stator current OC_1. In the flux diagram the vectors are the total flux OX_1, made up of the components OX_2, the rotor flux, and OX_l, the leakage flux. Thus, while OC_1 produces a flux OX_l, the current OC_m produces a proportionately much larger flux OX_2, since the flux measurement scale must remain the same. Now if we assume that these different ratios of flux to current in these two magnetic circuits hold for all values of OC_1 (that is for all loads), it follows that the ratio of $X_1 C$ to $C O$, which, geometrically, is the same as the ratio of $X_1 X_l$ ($= OX_2$) to OC_m, is constant. But from the condition of the equality of e_1 to V the flux O X_1 which produces e_1 is constant, and the line O X_1 is a fixed length. The point C is therefore a fixed point, and the triangles O C_m C and C C_1 X_1 are both right-angled triangles standing on fixed bases O C and C X_1 respectively. The loci of C_m and C_1 are therefore semicircles standing on the same bases. These semicircles have been drawn in the diagram, but it should be explained that for clearness the semicircle O C_m C has been made much larger relatively to the other semicircle than it appears in actual practice, in which it is so small that no large error is introduced by regarding C C_1 instead of C_m C_1 as the current equal and opposite to the secondary current C_2.

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* If this condition be not satisfied the actual current assumed to be flowing will be approximately obtained by equating the *ampere turns* in the stator and rotor, but the adjustment makes no difference in the theory propounded, and for the purposes of the diagram a correction for any difference in the number of turns must be made.

We are now in a position to deal with the circle diagram of an actual machine, and for this purpose we reproduce on Plate XIII. the Heyland diagram of a 150-H.P. three-phase induction motor having eight poles and designed to run on a 3,600-volt 50-cycle circuit. For this diagram the author is indebted to Mr. F. M. Denton. The stator and rotor are both star-connected, and the resistances (cold) were 1·28 ohm and 0·0136 ohm per phase. The experimental data are: (i.) No-load test, power 5,000 watts, current 5·47 amperes per phase, power factor Cos ϕ_0 0·147 (ϕ_0 = 81° 27′); (ii.) stand-still (or locked) test, kilowatts 54·8, current = 106 amperes per phase, power factor Cos ϕ_s = 0·166 (ϕ_s = 80° 33′). The line voltage in both cases was 3,600 volts, but the second test was actually taken at half-voltage.

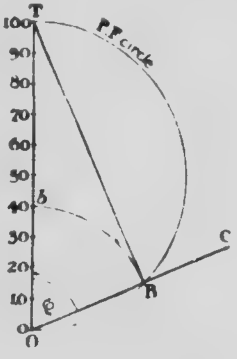


Fig. 784.—The Power-factor Circle

To draw the diagram the base or flux line O X is first set out and the volt line O T at right angles to it. For the power factor, and to avoid the use of trigonometrical tables, a large semicircle, marked the "P.F. circle," is turned on O T and its diameter divided into 100 for a percentage scale. Its use is explained in Fig. 784. For instance, if it be required to draw the current vector O C, whose power factor is 40 per cent. (Cos ϕ = 0·4), the line O b (= 40) is turned down to cut the circle at B, and O B produced is the required vector. Since O B T is a right angle, it is obvious that

$$\mathrm{Cos}\,\phi = \frac{\mathrm{O\,B}}{\mathrm{O\,T}} = \frac{40}{100} = 0{\cdot}4.$$

Draw now, Plate XIII., the line O C_s (= 106 amperes) through P_s on the P.F. circle, for which the power factor is 16·6 per cent.; this line represents the vector of the locked current. Similarly draw the vector O C_0 (= 5·47 amperes) with a power factor of 14·7 per cent. to represent the no-load current. By bisecting the line C_0 C_s at right angles the centre of the Heyland semicircle will be given on O X, and the semicircle C_0 C_s X can be drawn, fixing the positions of C and X. Any vector, such as O C_7 drawn from O to a point on this semicircle will give, on the scale of amperes, the input current for a given load; or, if this input current has been measured, the point C_7 can be found and the diagram used to deduce a number of other quantities for this particular load.

First, the power-factor can be found at once (*see* Fig. 784) from the point P_7, where the vector OC_7 cuts the P.F. circle. In this case OP_7 scales off as a power factor = 0·72 or 72 per cent. Next, since $C_7 \times \cos\phi_7 = C_7 c_7$, i.e. the vertical line, and since the supply voltage is known, this line $C_7\,c_7$, when referred to an easily ascertained scale, represents the kilowatts *input*, $\sqrt{3}\,V_7\,C_7\cos\phi_7$, since V_7 is the limb voltage of the star. A part of this scale is shown on the diagram alongside the ordinate $C_7\,c_7$.

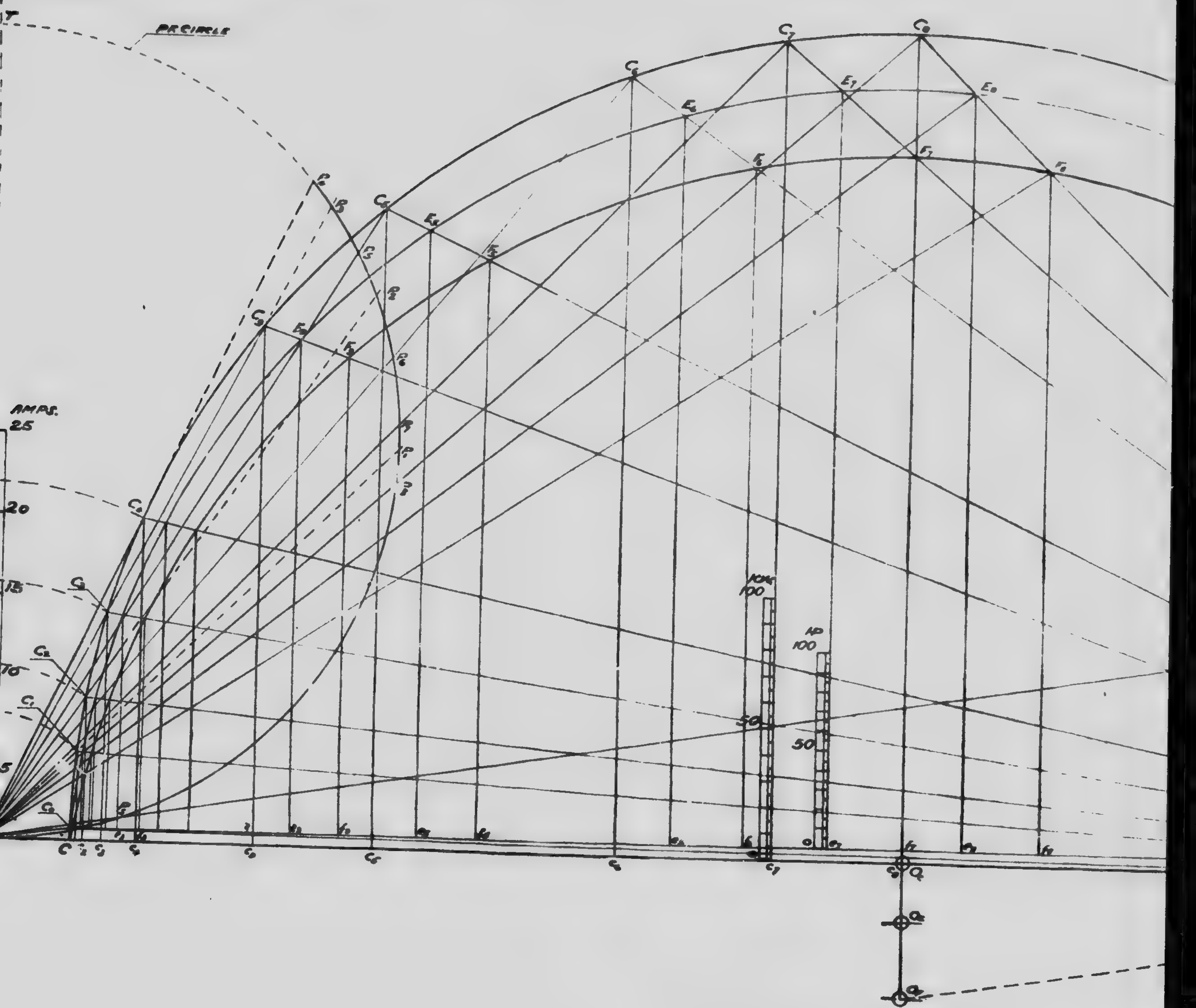
The no-load losses are equal to the no-load input, and are therefore measured, on the kilowatt scale, by the height of the point C_o above the line ON_1. These losses consist chiefly of the hysteresis and frictional losses, which are assumed to be, and are practically, constant at all loads. A horizontal line drawn through C_o parallel to ON will deduct from all the input ordinates the power lost in this way.

To allow for the voltage drop in the stator, which has, so far, been neglected, it should be recalled that $C_1 N_1$ (Fig. 783) represents the rotor flux due to voltage V. If $R_1 C_1$ of this voltage be lost owing to the resistance of the stator, the length $C_1 N_1$ must be reduced by an equivalent amount, for the phase relations will remain practically unchanged; therefore, in Plate XIII., if $C_7 E_7 = R_1 C_1 \times \frac{ON}{OV}$ be deducted, the remainder $E_7 N$ will be the rotor flux. If now an arc of a circle be drawn through $C E_7 N$ it can be shown that this arc is the locus of the points E for all loads. For $C_7 E_7$ is proportional to C_7, that is to OC_7 or to CC_7 very nearly; but the angle $C C_7 E_7$ is a right angle, and thus the angle $C E_7 C_7$ is a definite constant angle; it follows that its supplement $C E_7 N$ is also constant, and as all such angles stand on the constant chord CN, the points E must, by a well-known property of the circle, lie on an arc of a circle. This arc $C E_8 N$ is drawn so that the point E can be found for any load; its centre is at O_8.

Now the torque imparted to the rotor is proportional to the rotor current ($C_m C_1$ of Fig. 783) multiplied by the flux EN, or (since CC_1 varies as $C_m C_1$) it is proportional in this case to $CC_7 \times E_7 N$. But this product, since the vertical angle of the triangle $C E_7 N$ is constant, is proportional to the area of that triangle, and therefore to its altitude, since the base CN is constant. The power given to the rotor is proportional to the torque, since the angular velocity (that of the rotating flux) is constant. Of this power the amount cut off between c_7 and CN is expended in friction,

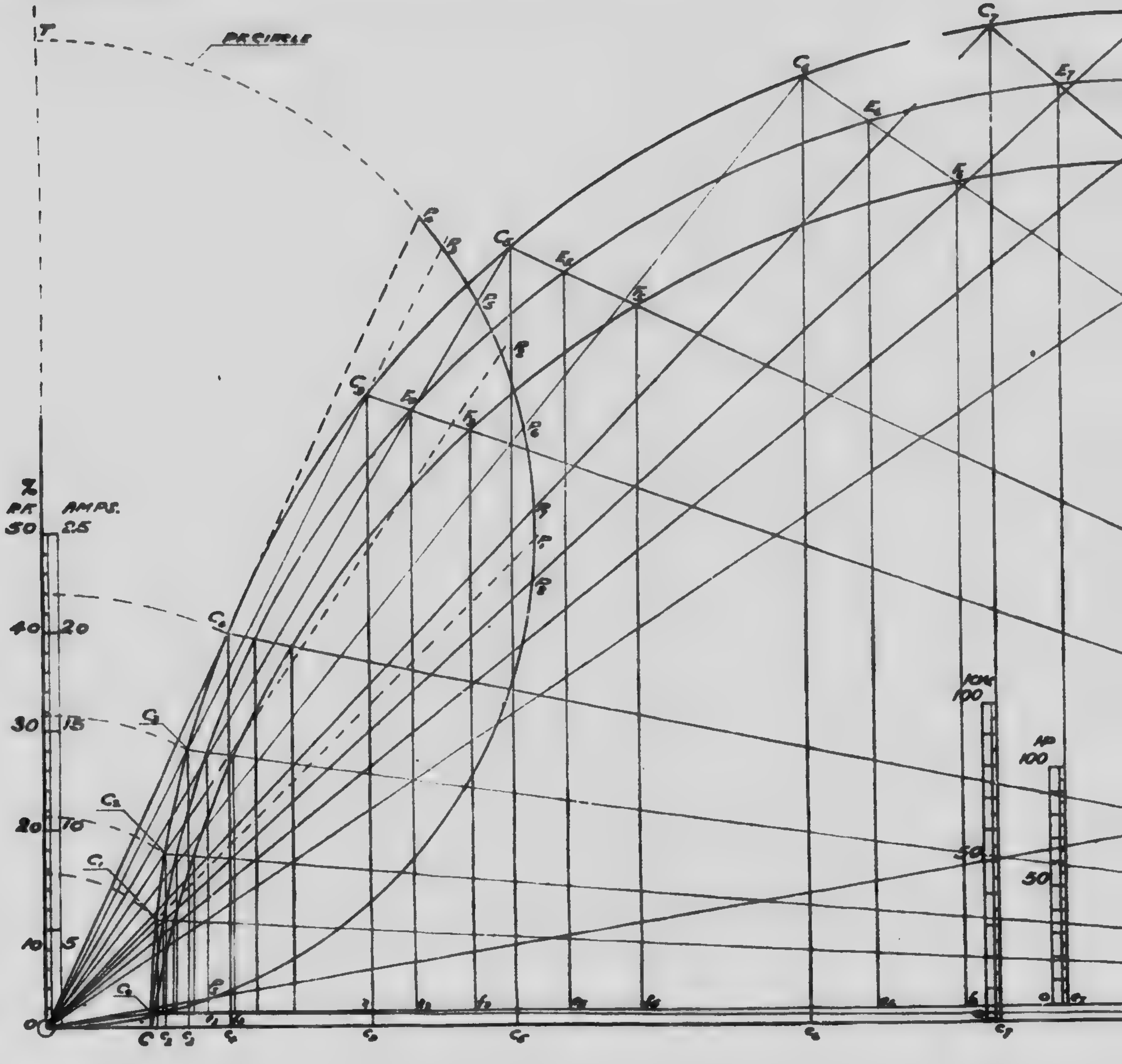
PLATE X

PLATE XIII.

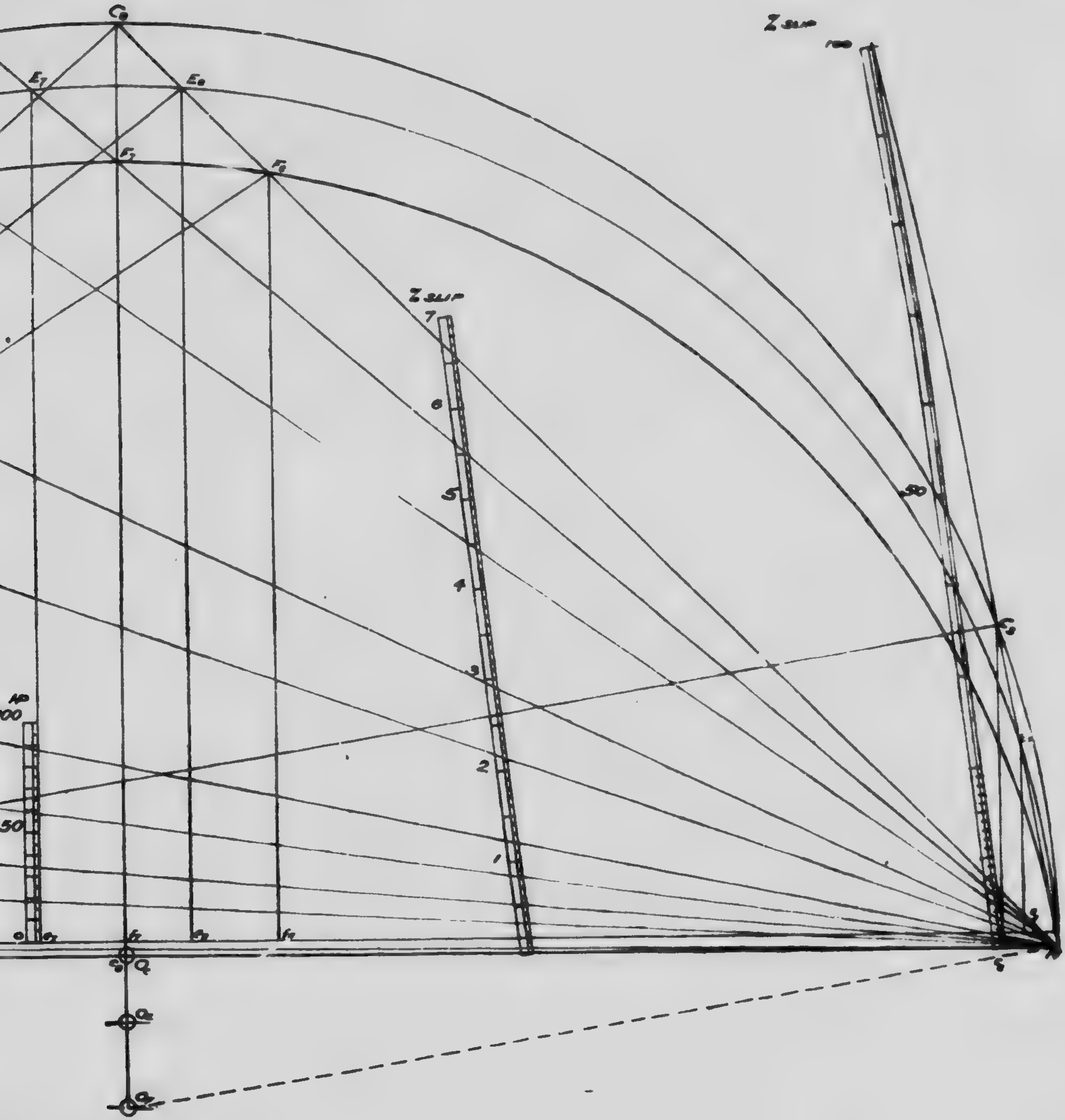


THE CIRCLE DIAGRAM OF AN INDUCTION MOTOR

PLATE XIII.



THE CIRCLE DIAGRAM OF A



AGRAM OF AN INDUCTION MOTOR.

windage, hysteresis, etc., and the balance, proportional to $E_7 c_7$, would be expended in driving the mechanical load on the shaft if the shaft rotated synchronously with the flux. The actual power given out, however, is diminished *pro rata* by the slip.

To allow for the slip it should be noted that the whole of the e_2 voltage in the rotor of an induction motor is used up in driving the current through the resistance R_2, and that therefore $e_2 = R_2 C_2$. If the speed of $E_7 N$ relative to the rotor were synchronous, we should have $\frac{OV}{ON} = \frac{e_2}{E_7 N} = \frac{R_2 C_2}{E_7 N}$. The actual speed of $E_7 N$ relative to the rotor is the slip, and therefore the ratio of e_2 (or $R_2 C_2$) to $\left(E_7 N \times \frac{OV}{ON}\right)$ is the slip. If, therefore, on Plate XIII, we scale $E_7 F_7$ off $E_7 N$ such that $E_7 F_7 = R_2 C_2 \times \frac{ON}{OV}$, then we know that $\frac{E_7 F_7}{E_7 N} = \frac{R_2 C_2}{E_7 N} \times \frac{ON}{OV}$ is the slip. Since $E_7 F_7$ is proportional to C_2 or to $C\,C_7$, then by the same reasoning as before we know that F_7 lies on the arc of a circle standing on $C\,N$ as a chord, and that circle is drawn on the diagram, its centre being O_F. Since $\frac{E_7 F_7}{E_7 N}$ is the slip,

$$\frac{E_7 N}{F_7 N} = \frac{\text{synchronous speed}}{\text{speed of shaft}}$$

and, therefore,

$$\frac{F_7 c_7}{\text{Power given out by shaft}} = \frac{E_7 N}{F_7 N} = \frac{F_7 c_7}{F_7 f_7}.$$

Hence $F_7 f_7$ represents the power given out by the rotor to the same scale that $F_7 c_7$ represents the power received by the rotor. The scale of horse power for the particular diagram is marked at the bottom of the ordinate $F_7 c_7$. Since for the locked rotor there is no mechanical output for the point C on the circle, the point F_s coincides with N, and therefore C N is a tangent to the F circular arc. It must not be overlooked that $F_7 c_7$ still represents the torque, and that the stand-still torque is given by $C\,c$, which shows how small the torque is for the enormous primary current $O\,C$.

We have by no means exhausted the Heyland diagram, and though the investigation may appear long, it has only dealt with the main quantities. We shall not, however, pursue the subject farther, except to point out that there is one point, C_4, on the circle at which the vector drawn from O is a tangent. At this point the power factor is a maximum, for all the other vectors must lie to the right of $O\,C_4$. This vector is, in fact, the full-load current. The maximum output is given by $F_7 f_7$.

For the machine dealt with in Plate XIII, the following particulars can be obtained from the diagram :—

Full-load line current .. = 22 amperes per phase
" power factor .. = 0·9
" slip .. .. = 1·2 per cent.
" output .. .. = 154 H.P.
" efficiency .. .. = 93 per cent
Overload capacity .. .. = 2·3 times full-load
Maximum load efficiency .. 85 per cent.

The conditions of the quantities for other loads can be ascertained from the following scale values

1 ampere .. .. .. = 0·12 inch.
100 volts .. .. .. = 0·624 inch
100 per cent. power factor .. = 6·0 inches
1 per cent. slip .. .. = 0·06 inch
or 1 per cent. slip .. .. = ·6 inch
10 kilowatts .. .. .. = 0·103 inch
10 horse-power .. .. = 0·144 inch.

Some of these scales are actually drawn on the plate.

Performance Curves from Circle Diagram.—As an example of the practical use of the diagram for predicting the performance of the motor under varying conditions of load, we give in Table VIII the readings taken from the diagram of (i.) input, (ii.) output, (iii.) efficiency, (iv.) torque as calculated for synchronous speed, (v.) power factor, (vi.) slip, and (vii.) speed. The first horizontal line of the diagram gives the particulars of the "locked" rotor tests, and the last horizontal line those of the "no-load" tests; it will be remembered that it is from these tests that the diagram has been built up. These data are plotted as curves in Fig. 785 in which the output calculated as horse-power is plotted horizontally and

TABLE VIII.—DATA FROM CIRCLE DIAGRAM FOR THREE-PHASE INDUCTION MOTOR, 150 H.P., 8 POLE, 3,600 VOLT

Current Input	Power Input	Power Output		Percentage Efficiency	[illegible] Synchronous [illegible]	Power Factor	Slip	R.P.M.
Amperes.	Kilowatts.	Kilowatts.	[illegible]		[illegible]	Per cent.	Per cent.	
106	160·7	0	0	0	862	17	100	0
76·3	320	262·5	354	82	501	67	6·55	701
66·6	316	267	357	84·5	500	72·2	5·48	709
61·75	290	266·5	349	87·1	374	77·7	4·41	717
40	246	222	297	90·4	312	85·5	2·9	728
36	200	183	245	92	254	88·8	2·11	734
21·05	123·7	115·2	154	93	158	90·5	1·2	741
15·8	87·3	80·4	107·5	92·3	106·5	85·8	0·81	744
10·65	54·5	40·25	53·8	92·4	66·6	82·5	0·5	746
7·75	33·7	29·0	38·8	86	30·2	70	0·3	748
5·45	4·98	0	0	0		14·5	0·04	749·7

he other factors vertically. The curves therefore show the relations the other quantities to the output, these being the relations which f most interest to users. The curves may be taken as typical of the performance of good modern induction motors with short-circuited rotors It should be borne in mind that the motor under consideration is rated for an output of 150 H.P., and therefore the parts of all curves to the rig

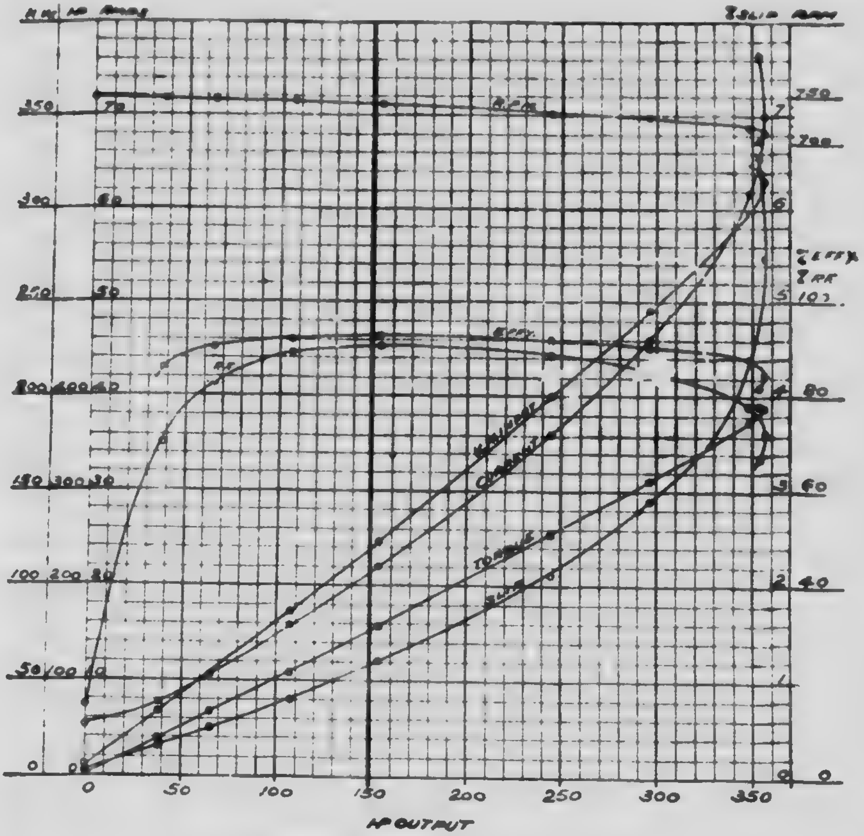


Fig. 7.5.—Performance Curves of [illegible] Induction Motor.

of the 150-H.P. line deal with the motor when running on an overload. The curves will repay careful study in the light of the particulars of induction motors given in the preceding pages.

The Circle Coefficient.—A cursory glance at the circle diagram, as set out on Plate XIII., will show that the relative values of the various lines or quantities dealt with in the diagram are intimately associated with the ratio of O C to C N, and that, as a matter of fact, if the length O N be fixed, which is a question of scale, and this ratio be known, the whole diagram can be geometrically constructed if the resistances and number of turns be known. The ratio referred to is known as the "circle coefficient" or the "circle-ratio"; it is usually denoted by the Greek letter σ, and is defined as

$$\sigma = \frac{OC}{CN} \text{ (Plate XIII.).}$$

The practical importance of σ lies in the fact that although it is not capable of exact predetermination, it can be calculated to a sufficient closeness of approximation from design data to enable the performance of a motor to be predicted from such data before the motor is built and available for experiment.

It is not surprising, therefore, that workers at the theory of the induction motor have devoted a great deal of attention to methods of calculating σ. Amongst these workers may be mentioned Behrend, Behn-Eschenburg Hobart, Biedermann, and others. From what has been said above, in describing how the diagram may be constructed and interpreted from experimental data, it will be realised that the magnetic leakage between stator and rotor is physically the determining factor, and therefore if iron had a fixed permeability for all fluxes this leakage might be readily calculable. We know, however, that permeability is a variable quantity, and that therefore the ratio of the leakage flux to the total flux of a particular motor will vary under different conditions. This constitutes the main difficulty in the predetermination of σ, for which the chief data are the depth, width, and number of the slots, the radial length of the air gap, the core length, the polar span, and minor points which affect the inductance of the circuit. Various methods and formulæ have been proposed, and Hobart in his book on "Electric Motors" tabulates the results of seventy-one cases, of which twelve refer to squirrel-cage and fifty-nine to slip-ring motors. Of these

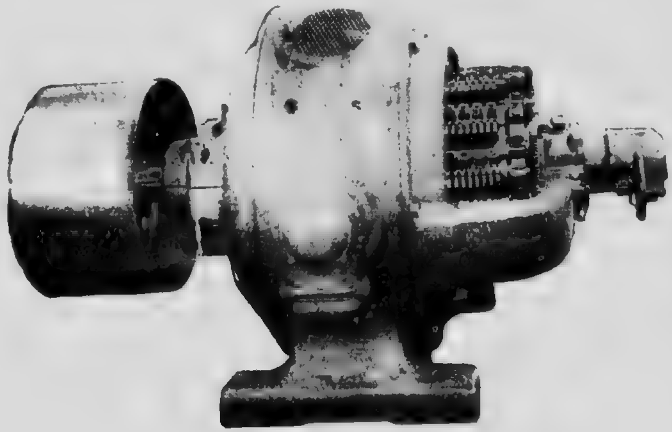


Fig. 786.—S.S.W. Three-phase Series Commutator Motor.

motors twenty (six squirrel-cage) were small and twelve (all slip-ring) were large, the remaining thirty-nine being of medium size. The differences between the observed values of σ and the author's method of estimating these values are carefully analysed, and the student who is interested should consult the table, the reproduction of which would carry us beyond the limits of this book. It may, however, be mentioned that the values of σ for the twelve squirrel-cage motors vary from 0·030 to 0·083, whilst for the fifty-nine slip-ring motors the variation is from 0·022 to 0·176, but for only eight of the fifty-nine is σ above 0·100. The value of σ for a squirrel-cage motor is taken by Hobart as being 0·8 of the value for a slip-ring motor, for which the other data are the same.

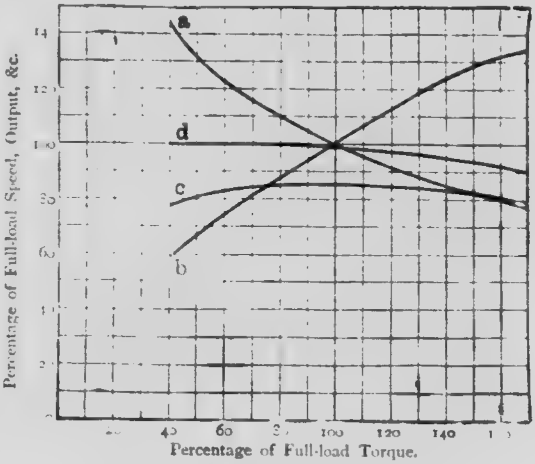


Fig. 787.—Performance Curves of S.S.M. Series Commutator Motor.

V.—POLYPHASE COMMUTATOR MOTORS

These motors derive their descriptive title from the fact that their rotors consist of ordinary continuous-current armatures provided with a commutator. The stator is similar to that of an ordinary three-phase induction motor. As already mentioned (*see* page 689), they fall into two main types, namely (i.) those in which an external voltage from the supply circuit is impressed upon the armature, the connections to the supply circuit being either a series or a shunt connection; and (ii.) those in which the armature revolves with the brushes short circuited. The last-named are generally known as "repulsion" motors.

In view of the fact that one of the great advantages of alternate-current machinery is the absence of the expensive commutator essential in continuous-current working, it would appear, at first sight, that the deliberate incorporation of a commutator in an alternate-current motor is a distinctly retrograde step, as adding to the prime cost of the machine and also bringing other well-remembered troubles in its train. So varied, however, are the uses to which electric motors can be put, and so diverse the requirements of service, that advantages of speed regulation, convenience in starting conditions, high power factor, and other matters may, and in one way or another do, combine to render the polyphase commutator motor the best solution for particular problems. Put otherwise, it may be said that the development of the commutator motor is due to the ascertained limitations of the induction motor.

Series Commutator Motors.—The general appearance of one of these motors, as manufactured by the Siemens-Schukert Werke ("S.S.W."), who, following Messrs. Siemens and Halske, have been pioneers in their development, is shown in Fig. 786, which is an illustration of a 120-B.H.P. motor designed to run at 750 R.P.M. on a 2,000-volt, 50 ∿, three-phase circuit. There are three brush spindles for each pair of poles of the machine, and speed control is obtained, as will be explained presently, by rocking the brushes. The performance curves for this motor are given in Fig. 787, in which (*a*) speed, (*b*) output, (*c*) efficiency, and (*d*) power factor are plotted as percentages of their normal values against torque similarly plotted. It will be noticed that the power factor is practically unity from 40 per cent. of full load up to full load, and only sinks to 0·9 for a 65 per cent. overload. The speed-torque curve is similar to that of a series continuous-current motor (*see* Fig. 574, page 604, Vol. I.), though the range is not so great, being from 140 per cent. to 80 per cent. of normal speed between the above limits. The efficiency varies between 80 and 85 per cent. between the same limits, which is fairly good but better results can be obtained with an induction motor (*see* Fig. 776, page 757).

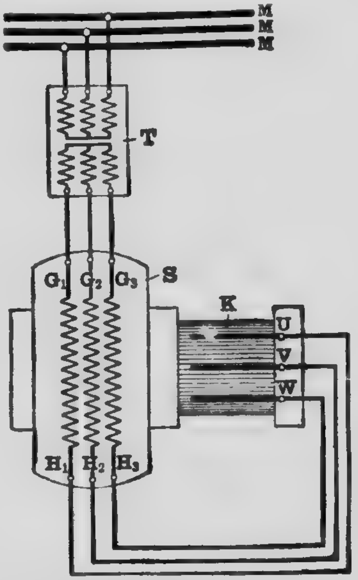


Fig. 788.—Connections of Series Commutator Motor to Mains through Transformer.

The connections of such a motor to high-voltage mains are shown diagrammatically in Figs. 788 and 789. For reasons similar to those which hold with continuous-current generators and motors, only a comparatively low voltage can be used on the commutator of the armature. These reasons do not, however, apply to the stator, and therefore the necessary step-down transformer, where the stator and armature are in series, which is the case with which we are now dealing, can be placed either between the mains and the stator as in Fig. 788, or between the stator and the armature as in Fig. 789. In both figures M, M, M are the high-voltage mains and T is the step-down transformer; G_1H_1, G_2H_2, and G_3H_3 are the terminals of the stator, K is the commutator, and U, V, W are the brushes, there being three sets of brushes to each pair of poles. The placing of the transformer between the stator and the armature enables a smaller transformer to be used, as it has only to handle the energy supplied to the armature, whereas in the other position it must handle the whole energy supplied to the motor. On the other hand, the arrangement in Fig. 789 requires a high-voltage winding on the stator, and this may be more costly than a low-voltage winding.

To secure a greater range of speed than that referred to above, a second set of brushes, which can be rocked independently, is sometimes placed on the commutator. This complicates the mechanical design, and increases the losses due to brush friction; but it renders it possible to run at any speed from dead slow to considerably over the normal speed at full load. Such a motor is shown in Fig. 790, which is from a photograph of a 50-B.H.P. motor designed to run at a normal speed of 750 R.P.M. on a 50 ∿ circuit, but with a speed range from 40 to 1,000 R.P.M.

The mode of action of these motors depends on principles already discussed, and may be readily explained in an elementary manner as follows, the case of a three-phase motor being taken as being the most usual. The stator being wound like the stator of a three-phase induction motor, produces a revolving magnetic field of the designed polarity when supplied with the appropriate three-phase currents in the usual way. If now an ordinary closed circuit continuous-current armature be supplied with three-phase currents through brushes spaced so as to give the same number of poles, i.e. placed 120 electrical degrees apart, it will, whether the armature be stationary or rotating, give a magnetic field of similar polarity rotating at the same speed, and with a definite space relation to the rotating field of the stator depending upon the position of the brushes or coils under commutation with respect to that field.

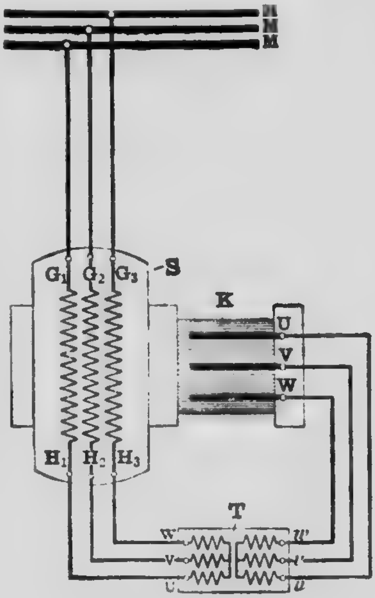


Fig. 789.—Connections of Series Commutator Motor direct to Mains.

One of the possible and usual methods of connection for the second set of brushes is shown in Fig. 791, in which the step-down transformer is between the mains and the motor. In some designs both sets of brushes can be rocked independently or together; in others one set is fixed and the other is movable, and is used alone for regulating the speed, if supplied with currents derived from the same supply circuit. If both stator and armature in their proper relative positions be supplied with these three-phase currents, then the two fields will be superposed, but they will still both rotate at the same speed, preserving an invariable time-phase relation. In addition, however, to the phase relation in respect to time, there is the phase relation with respect to space, determined by the positions of the lines of brushes with respect to the leading-in points in the stator circuits. This space phase-difference can therefore be altered by rocking the brushes, for which, if the ampere-turns on the stator and armature are equal, there is one position in which the two fields would neutralise one another, and the torque between the stator and the armature would be zero. With the brushes exactly 180° from this position there would again be no torque, for similarly directed currents would be opposite one another always over the whole periphery, the two magnetic fields coinciding and reinforcing one another. In all other positions of the brushes there will be a resultant rotating magnetic field, which will interact with the currents in the armature and tend to cause the latter to rotate. It has already been remarked that such rotation has no effect upon the space positions of the rotating armature field.

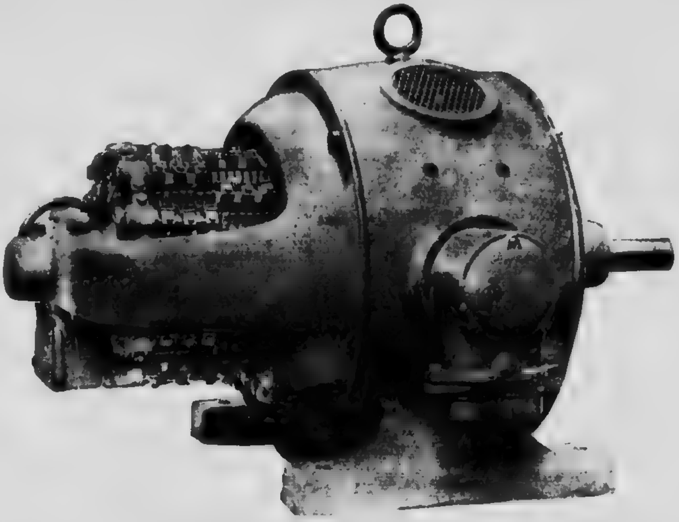


Fig. 790.— S.S.W. Three-phase Series Commutator Motor, with Double Sets of Brushes.

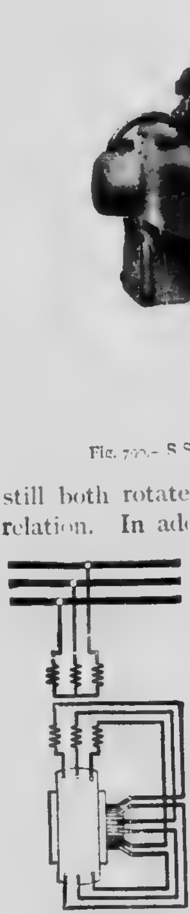


Fig. 791. — Connections of S.S.W. Motor, with Double Set of Brushes.

In the foregoing elementary remarks, secondary effects, such as magnetic leakage, the currents in the coils short-circuited by the brushes, copper and iron losses, etc., have been neglected. Whilst these secondary effects, whose investigation would lead us too far into the mathematics of the subject, may evidently be important in determining the limits within which a useful or efficient mechanical effort can be obtained by rocking the brushes, it is evident that there must be many positions of the latter which, in a properly designed motor, will give the desired results. The relation between the brush position and the torque is exhibited by the curves in Fig. 792. In these curves the angular position of the brushes is plotted horizontally in electrical degrees, and the torque vertically. The zero for the horizontal scale is taken from the brush position in which the magnetic fields are in the same phase position, and are therefore additive. The maximum torque is attained with the brushes 130° from this zero, and this is the position used for starting the motor. The running position with normal torque is with the brushes 150° from the zero.

The speed can be varied by altering the position of the brushes or by varying the terminal pressure, but the first method is the simpler; the second method involves the use of costly apparatus. The great advantages claimed for this type of motor are the great range of speed possible and the ease with which it can be controlled, and that, with a similar speed-torque characteristic, the control is more economical than in the case of the continuous-current motor.

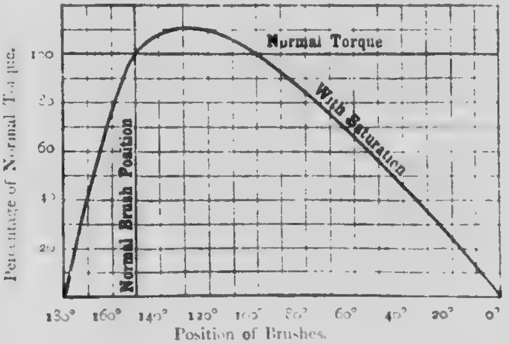


Fig. 792.—Dependence of Torque upon Brush Position.

This type of motor is also very flexible in its adaptability to the working requirements of various rather difficult industrial power applications, and if space permits we shall refer to some of these later.

Shunt Commutator Motors. These have been developed by Winter-Eichberg for three-phase working. They have a speed-torque characteristic similar to that of a shunt-wound continuous-current motor; in other words, the maximum speed is attained when the motor is unloaded, and falls off slightly only and gradually along a straight line as the load is increased. This is advantageous in certain applications where a nearly constant speed is desired. The connections are shown in Fig. 793; as the two circuits are quite independent, a transformer is only inserted between the armature and the high-voltage mains. The no-load speed can be adjusted by varying the pressure on the brushes, by tappings on the secondaries of the transformer. The motor is manufactured by the A. E. G. Electric Co., Limited, and in some of its modifications the currents for the armature are taken from tappings on the stator windings. In other modifications the currents from the transformer are led through "compensation" windings on the stator before reaching the brushes.

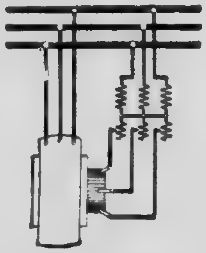


Fig. 793.—Connections of a Shunt Commutator Motor.

In a more recent type of three-phase shunt commutator motor, Schrage dispenses with the transformer of Fig. 793, and feeds the supply current direct into a delta-connected primary winding P on the rotor through slip rings, as shown in Fig. 794. A secondary winding R, which may be called the regulating winding, is connected to a commutator not shown in the diagram, to which three pairs of brushes are applied. Each pair of brushes, such as $a_1\,b_1$, is connected to one of the phase windings on the stator, the three windings of which are thus delta-connected together through the commutator and a section of the windings R, and it is these sections which act as the compensation windings in the other form of machine. Of the three pairs of brushes, a_1, a_2, and a_3 are carried on one brush rocker, and b_1, b_2, and b_3 on another. The brush mounting can be seen in Fig. 795, which is from a photograph of a Schrage motor as built by the Allmanna Svenska Elektriska Aktiebolaget of Sweden. When the two brushes $a\,b$ of a phase stand on the same commutator bar the stator coils are short-circuited, and the machine runs as an induction motor at a little below synchronous speed. By separating the brushes in one direction or the other the machine can be made to run at a great variety of speeds, ranging from 50 per cent. below to 50 per cent. above synchronism. The no-load speed at which the motor runs under these conditions is given by the equation

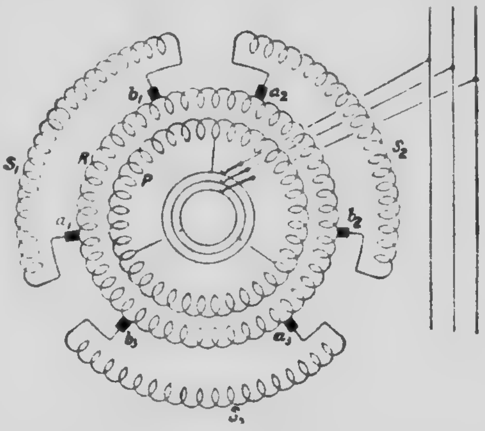


Fig. 794.—Connections of Schrage's Three-phase Shunt Commutator Motor.

$$n = \frac{60\,f}{p} \cdot \frac{T_S \pm T_R}{T_S}$$

where *f* is the frequency, *p* the number of pairs of poles, T_s the number of turns in each of the secondary windings S, and T_R the number of effective turns between each of the pairs of brushes *a b*. When *a* and *b* coincide $T_R = 0$, and *n* is the synchronous speed of an induction motor. The brush-shifting arrangements are necessarily complicated, as can be seen in Fig. 795, which shows a 12-pole motor which runs at from 200 to 800 R.P.M. on a 50-cycle 220-volt circuit with a maximum output of about 50 H.P.

For each position of the brushes the machine has a drooping, shunt, speed characteristic, with an increasing power factor as the load increases. For the lowest speeds, however, the power factor is very low, and the speed regulation poor. The prime cost of the machine itself is high, but as it is self-contained, and requires neither transformers nor expensive starters and controllers, the prime cost of the total equipment is lower than in some other systems.

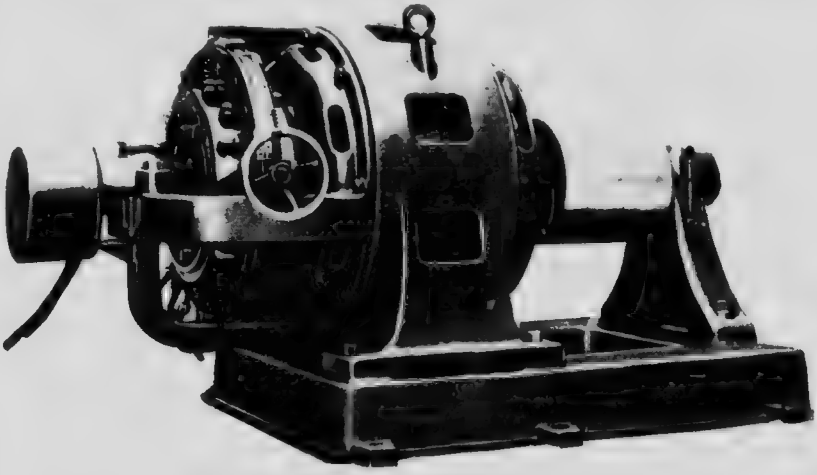


Fig. 795.—Schrage's Three-phase Shunt Commutator Motor.

Three-phase Repulsion Motors.—In the commutator motors we have just described currents from the supply circuits are introduced into the armature, where they are superposed upon induced currents caused by the variation of the magnetic field in which the armature conductors are placed, or, to put it otherwise, where they are modified by inductive E.M.F.s set up by the same cause. In the induction motor the whole of the currents in the rotor are induced currents flowing in the circuits of a squirrel-cage winding or in the more definite circuits of a wound slip-ring rotor. In the repulsion motor the slip-rings of the wound rotor of the induction motor are replaced by a commutator on which are placed brushes interconnected, so that if such connections were made in a continuous-current machine it would be short-circuited. The general effect, therefore, is that the induced currents are constrained to flow in more definite paths than in a squirrel-cage winding, and the interaction between these currents and the magnetic fluxes causes the armature to rotate, and thus leads to a conversion of electric into mechanical energy.

Many years ago the repulsion motors which were built were single-phase motors to which we shall refer later; but more recently A. Heyland, who has for many years been a pioneer in alternate-current motor work, has constructed three-phase repulsion motors. In the simplest of these motors the stator is fed with ordinary three-phase currents, and the armature is supplied with three pairs of short-circuited or connected brushes, as shown in Fig. 796, which closely follows one of Heyland's figures, but is drawn for a four-pole instead of a two-pole field, and therefore shows six pairs of short-circuited brushes. The stator is not wound in quite the same way as an ordinary induction motor stator, which, as represented in Fig. 796, would produce a two-pole rotating field, as explained elsewhere, but with a chord winding producing three definite poles in each half of the machine. When the line currents flow in this winding they produce a magnetic system of three super-imposed alternating fields with their axes inclined to one another at 120 electrical degrees. The short-circuiting brushes are placed so that the angular distance spanned is a little less than 120 such degrees. Under these circumstances, as the alternating flux varies in the space spanned by a pair of brushes, E.M.F.s will be set up in the armature conductors in that space such as will give rise to currents whose circuit is completed through the short-circuiting conductor joining the two brushes. The currents will be at right angles to the field flux, and mechanical forces tending to drive the armature round will be set up.

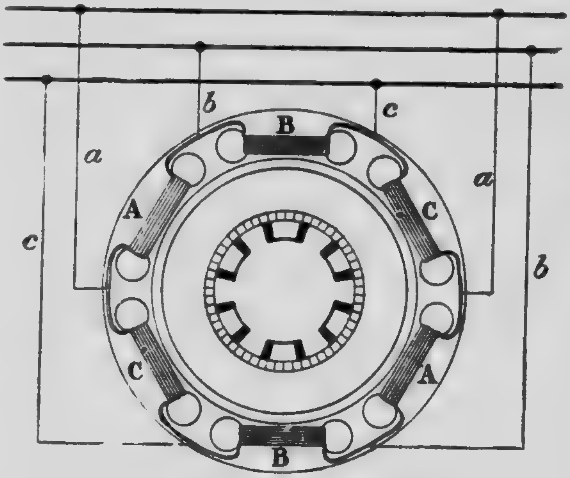


Fig. 796.—Connections of a Three-phase Four-pole Repulsion Motor.

In Heyland's earlier two-pole motors of this type the brushes were mounted so that they could be moved all together or in two sets of three.

each set being movable relatively to the other set. In still more recent types it has been found possible to improve the power factor by placing the fixed and movable brush of each pair about 160° apart, as shown in Fig. 797, instead of less than 120°, as in Fig. 796. In this way the armature fields due to the conductors between each pair of brushes overlapped, producing a compensating effect similar to that of the stator compensating coils in an ordinary commutator motor. In Fig. 797 the circle S stands for the stator and the circle R for the rotor; the line currents are fed into the stator at the points 1, 2, and 3.

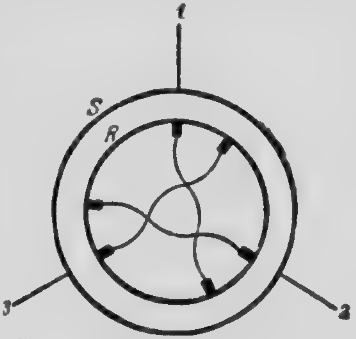


Fig. 797.—Brush Connections in a Three-phase Commutator Motor.

The effects on the power factor are shown graphically in Fig. 798, which gives the results of experiments on a motor with a rated output of 8·84 H.P. Curve *a* is for the motor run as a short-circuited squirrel-cage motor; for this purpose the segments of the commutator were directly connected right round. The power factor varies from 0·28 at no load to 0·83 at over full load. Curve *b* is for the brushes exactly 120° apart; that is, the two adjacent brushes of consecutive pairs in Fig. 797 have been made to coincide, with the result that the six brushes become three, and the effect is to convert the armature into a rotor with three short-circuited slip-rings. The power factor is appreciably improved, and now varies from 0·4 at no load to 0·9 at over full load. In curve *c* the short-circuiting brushes are separated by 160°, as shown in Fig. 797, the fixed brush of each pair being at the neutral point. The effect on the power factor is remarkable, since it now varies only between 0·7 at no load and 0·98 at over full load. Lastly, curve *d* shows the effect of moving the fixed brushes from

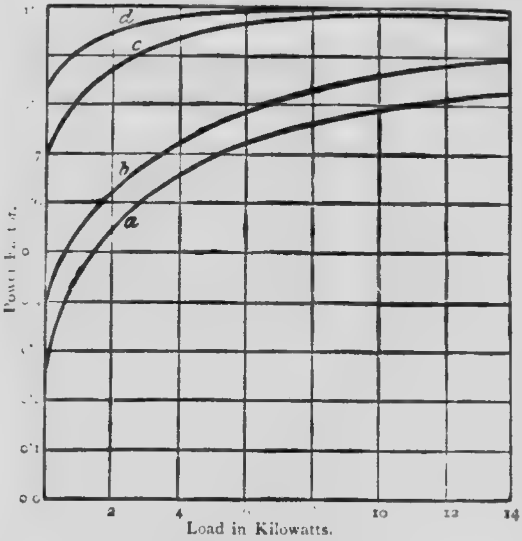


Fig. 798.—Power-factor Curves.

the neutral position 40° forward in the direction of rotation. The result now is that the power factor is practically unity for a wide range of load, and only sinks to 0·84 for no load.

Repulsion motors of this type are very similar to series commutator motors in size and efficiency, but the former is a nearly synchronous machine, whilst the series motor can be run at speeds up to 50 per cent. above synchronism. At speeds below synchronism the repulsion motor characteristic is much the same as that of a series machine, but close to synchronism it has a shunt characteristic; it has also a good starting torque.

Induction and Commutator Motors in Cascade.—A very important utilisation of the polyphase commutator motor is to run it in cascade with a polyphase induction motor. Some space has already been devoted (*see* pages 749 and 751) to the running of induction motors in cascade, and also (*see* pages 752 to 756) to using the cascade principle within the limits of a single motor, the main object being in each case to obtain a greater range or variety of speed.

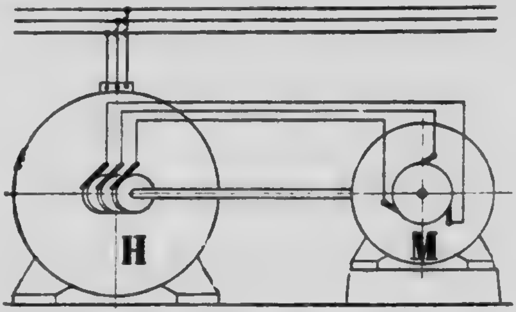


Fig. 799.—Diagram of Kramer's Cascade Connection.

The problem in the present case may, however, in the first instance be viewed from a somewhat different standpoint. One of the methods of starting induction motors (*see* pages 727 to 736) is by inserting resistances in the rotor circuits, and this method is extensively used. These resistances absorb energy and waste it in heat, whereas if the energy could be retained in a convenient form the efficiency of the arrangement would be increased. Replace, therefore, the dead resistances by a commutator motor which can absorb the energy and convert it into useful mechanical work which can be returned to the rotor of the induction motor, either by the two rotors being coupled on the same shaft or, more wastefully, by their being belt or gear connected.

The simplest arrangement, as proposed by Kramer, is shown in Fig. 799; H is an induction motor shown diagrammatically as coupled both mechanically and electrically to the commutator motor M. The mechanical coupling is that both rotors are on the same shaft, and electrically the slip-rings of H are connected to the brushes of M.

The chief property of the commutator motor which makes it valuable for this purpose is that a change in frequency of the currents supplied does not necessitate a change in speed. The currents from the rotor of H have, as explained elsewhere, the frequency of the slip with which its rotor is running, and therefore vary from the supply frequency at standstill to that of the small percentage slip at the full running speed. The commutator motor M can absorb the currents at all these frequencies and convert their electrical power into mechanical power.

The above method is effective if the speeds dealt with are moderately high, but for low speeds the motor M is unnecessarily expensive, and therefore Dr. Scherbius proposed that instead of the power absorbed by M being returned to H as mechanical power, it should be returned as electrical power. For this purpose the shafts of H and M are disconnected, and an induction generator G (Fig. 800) is coupled to and driven by M, the stator of the generator being connected to the supply mains. Such a generator is simply a squirrel-cage induction motor, driven above synchronous speed. As already explained (*see* page 741), under these circumstances the induction motor becomes a generator, and if connected to live mains the currents generated will take the frequency of those mains to which they will contribute electrical power.

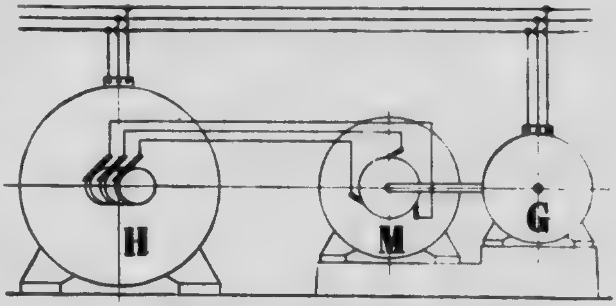


Fig. 800.—Diagram of the Scherbius Cascade Arrangement.

The various arrangements devised by Dr. Scherbius have been developed by Messrs. Brown, Boveri, and Co., of Baden, Switzerland, to whom we are indebted for Figs. 799 and 800. The commutator motors used in Fig. 800 may be either shunt or series machines, though in the latter case the brushes should have a fixed position. The shunt motor used will, of course, have compensating coils, and by varying its excitation a wide range of frequencies can be imposed on its supply circuit, which is the rotor circuit of the induction motor. To each of these frequencies there corresponds a definite speed (or slip) of the induction motor, whose speed can therefore be controlled by simply altering the excitation of the shunt commutator motor.

Commutator Motors generally.—The distinction between series and shunt polyphase commutator motors on the one hand and repulsion motors on the other, is one which the development of the subject tends to obliterate, even if it be not already obsolete. The elementary theory of commutator motors will be more conveniently taken in connection with single-phase machines, and the reader should refer to that sub-section (*see* pages 800 to 809) before reading the following paragraphs.

The subject of polyphase commutator motors owes much to Mr. V. A. Fynn, who has been an original worker in it for many years. Fig. 801, due to him, was used in a contribution to a discussion at the Institution of Electrical Engineers. The figure illustrates diagrammatically a bipolar commutator motor constructed for a two-phase supply introduced by the leads P_1 and P_2. The nomenclature used in lettering the diagram is neat and convenient. In the first place the rotor is assumed to have a gramme-ring winding on which the brushes directly rest, so that no question can arise of the influence and inductance of the connections between the commutator and the windings. The rotor winding is also assumed to be such that a current passing in at one brush and out at the diametrically opposite brush produces a flux directed from the first to the second brush. The distributed stator windings are represented by cylindric spirals having axes which coincide with the resultant magnetisation produced by the winding represented.* A stator winding N is one producing a flux opposed in direction to the armature reaction flux of the brushes on its axis, and may be referred to as a neutralising winding. It corresponds to the interpoles of a continuous-current machine. A stator winding marked F is one producing the motor and torque field, and may be referred to as an excitation winding. The brushes which carry currents producing only working or armature ampere-turns are designated by the letter *a*, and are shown black; whilst brushes—none of which appear in this particular figure—which carry currents producing excitation as

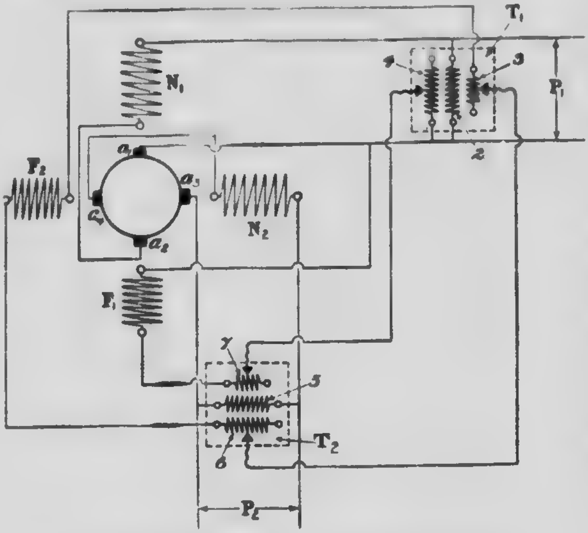


Fig. 801.—Diagram of Fynn's Two-phase Commutator Motor.

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* It may be criticised that in the actual figures the spirals drawn do not clearly represent the direction of the circulation of the current, but the context shows that a clockwise circulation when looking from the entrance terminal is intended.

well as armature ampere-turns are shown sectioned, and are designated by the letter *b*.

In Fig. 801 T_1 and T_2 are two transformers with their primaries 2 and 5 respectively bridged across the supply leads P_1 and P_2. The neutralising coil N_1 and the brushes $a_1\,a_2$ are in series across the first phase P_1, whilst the neutralising coil N_2 and the brushes $a_3\,a_4$ are similarly in series across the second phase P_2. The field coils which have shunt windings have more complicated cross connections. Thus the coil F_2, at right angles to and giving the motor flux corresponding to the brush axes $a_1\,a_2$, receives its chief supply from the secondary 6 of the transformer T_2, but also receives a small compensating voltage from the secondary 3 of the transformer T_1. Similarly the coil F_1, which gives the motor excitation for the brush axes $a_3\,a_4$, receives its chief voltage from the secondary 4 of the transformer T_1, and a small compensating voltage from the secondary 7 of the transformer T_2.

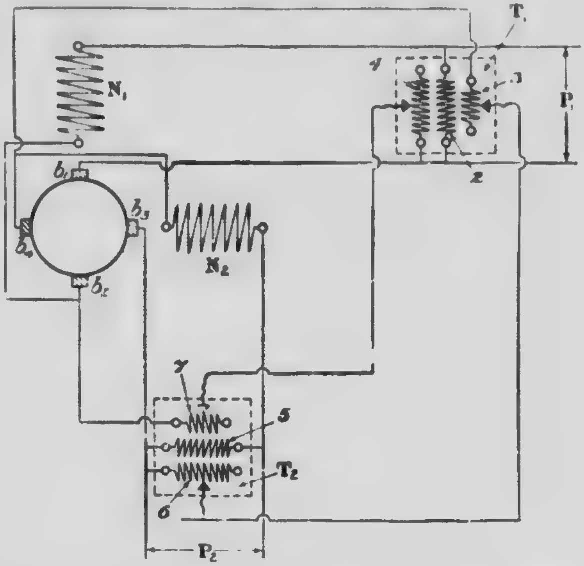

Fig. 802.—Fynn's Two-phase Commutator Motor with Armature Excitation.

The speed of the machine is adjusted either (i) by changing the voltage impressed on the armature circuits or (ii) by changing the excitation voltages derived from the secondaries 6 and 4. The power-factor of the machine is adjusted by changing the value of the compensating voltage impressed on each excitation winding, and derived from the secondaries 7 and 3 respectively.

In this way a wide range of speed and good power factors can be obtained, but the method has the disadvantage that it requires four distinct windings on the stator for the two-phase supply illustrated, and would require six such windings for a three-phase supply. A simplification can be obtained by abolishing the excitation coils F_1 and F_2 and by utilising the rotor or armature currents to give the flux necessary for the speed electromotive forces. The simplification is shown in Fig. 802, which is similar to Fig. 801, but with the stator excitation coils omitted, and the brush connections changed to give the right direction to the magnetic fluxes. A motor so connected becomes self-compensating, especially at the synchronous speed, but has the disadvantage that the heavier part of the load falls on the rotating part of the machine. The interesting subject of rotor excitation is referred to later in dealing with the theory of single-phase commutator motors.

The subject opened up by the foregoing paragraphs is a large one, to which a great deal of attention has been directed. The possible variations and extensions of the details are numerous, and some of them important, but pressure on our space precludes us from carrying the subject farther. Excellent results have been obtained, both as regards speed control and also as regards the favourable effect on the power factor. For large powers, where the transmission system offers an alternate-current supply, the system is cheaper than conversion from alternate currents to continuous currents, and the use of the latter in a continuous-current motor.

VI.—MONOPHASE INDUCTION MOTORS

In Chapter XVI. of Vol. I. the various types of motors available for use with monophase alternate currents have been summarised. For our present purpose—that of a brief description of modern monophase motors, exclusive of traction motors, which will be treated separately—these types may be confined to two, namely (*a*) induction motors (*see* Vol. I., page 617 *et seq.*), and (*b*) motors with commutating armatures (*l.c.* page 608). The former of these, as being far the more widely used for other than traction work, will now be considered.

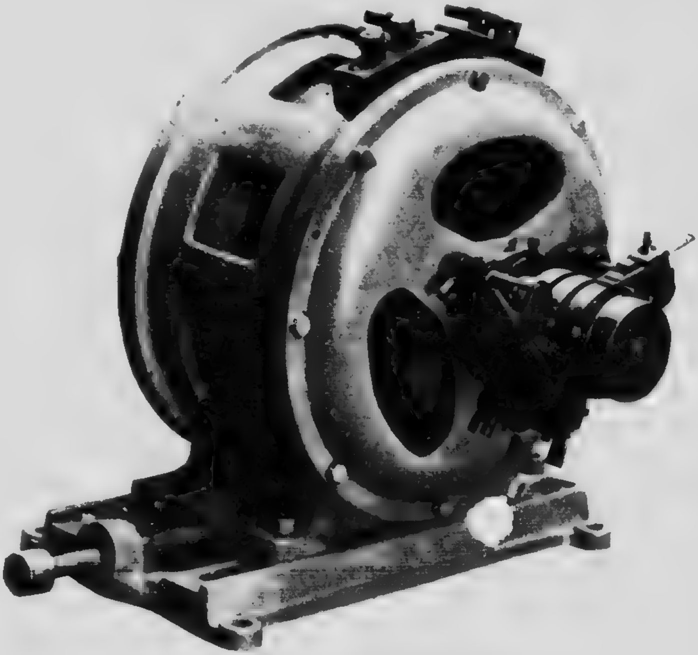

Fig. 803.—The Heyland Monophase Motor.

Monophase Induction Motors. It will be remembered that these are nearly synchronous motors with squirrel-cage or wound short-circuited tors running almost in step with the alternate magnetic field of the stator in which they are placed. This field, considered alone, does not tate, but is fixed in space and simply grows, diminishes, and reverses in step with the changes of the current supplied. When, however, the rotor is running at its proper speed, the magnetic reaction of the tor in combination with the stator produces a curious kind of rotating field.

It is, however, necessary to have some method of running the rotor from rest up to synchronism, for without some assistance it cannot take power from the stator until synchronism has been nearly attained.

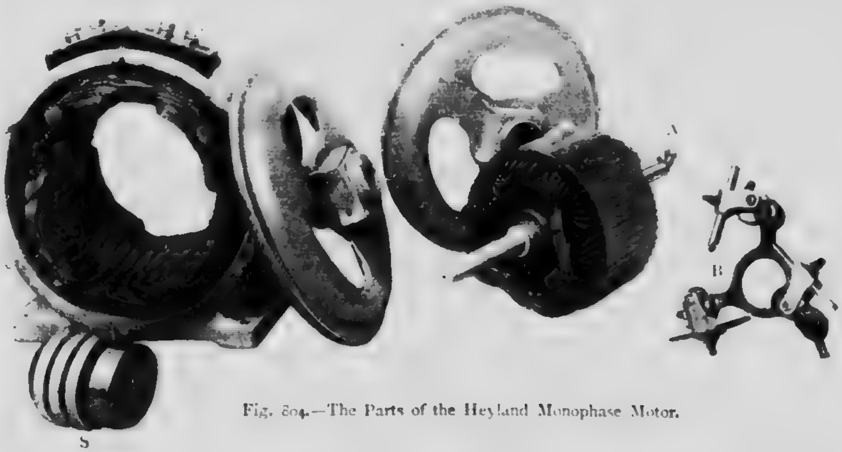

Fig. 804.—The Parts of the Heyland Monophase Motor.

The method adopted for starting the motor therefore forms an essential part of the design, and it will be more convenient to deal with it in each case when describing the motor itself rather than to relegate the different methods to a special section, more especially as these methods, almost without exception, make use of the same device—namely, that of producing for starting purposes a more or less regular rotating field by "splitting the phase" of the monophase current. This device has already been fully referred to, on a very different scale, in dealing with certain forms of *synchroscopes* (*see* pages 402 to 410 *ante*).

The Heyland Motor.—A monophase motor of the induction type which has played an important part in the development of these motors and may still be regarded as a standard type is the Heyland motor, shown complete in Fig. 803 and dissected in Fig. 804. It consists of a four-pole stator with auxiliary starting coils and a wound rotor with star-connected three-phase circuits, the ends of which are brought out through the hollow shaft, as seen at A (Fig. 804), and connected to an overhung set of slip rings S, which with their brushes B allow resistance to be introduced into the rotor circuit to increase the starting torque, as in polyphase motors. In fact, for starting purposes this is a diphase motor with a triphase rotor.

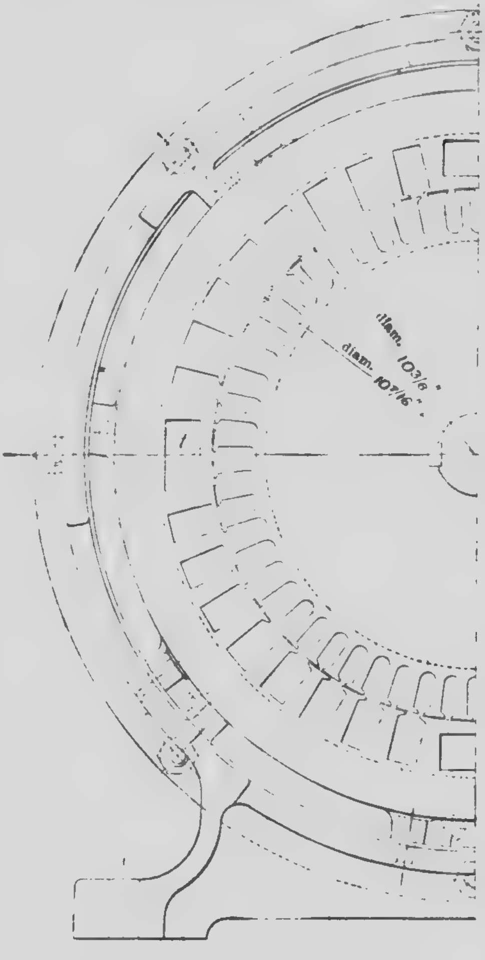

Fig. 805.—Magnetic Circuit of Heyland Motor.

Details of the magnetic circuit, showing the stator and rotor stampings, are given in Fig. 805. Each quadrant of the stator core contains eight slots, partly closed by overhanging teeth, and a relatively large tunnel *t*. The slots are used for the ordinary working coils, and the tunnel for the auxiliary starting coils. Magnetically, the iron in front of the tunnels provides the pole faces for the field when the motor is running under load with the auxiliary coils not in use. The scheme of winding is given diagrammatically in Fig. 806, which, however, only shows six slots per quadrant instead of eight in the actual case depicted in Figs. 804 and 805. In the latter, four slots on each side of each tunnel are used for the magnetising coil, which encircles the iron at the tunnel, thus producing the four-pole field, the connections being as shown in Fig. 806. The tunnels are used for four auxiliary coils, shown by dotted lines in the figure.

For starting, the two circuits of the stator are put in parallel on the monophase mains by an ordinary double-pole switch, a single-pole switch in the auxiliary circuit at S_2 (Fig. 806) also being closed. At the same time, the full starting resistance is introduced into the rotor circuit through the slip rings and an ordinary three-phase stepped starting rheostat, such as is described on page 730. The connections are given fully in Fig. 807, in which the various circuits of the stator, the rotor, and the starting resistances are shown diagrammatically with the switches in the starting position ready for the closing of the main switch. When the motor has run up to about full speed the resistances in the rotor circuits are gradually reduced by turning the switch S_4 in a clockwise direction until the slip rings are short - circuited. The diagram in Fig. 807 indicates the arrangements used when the motor is required to start light or with no load; in this case a resistance R is introduced into the running circuit of the stator to cut down the starting current, and when speed has been attained this resistance is short-circuited by the auxiliary switch S_2 being automatically thrown over from left to right at a predetermined point as the switch S_3 is moved round. By this movement, not only is the resistance R short - circuited, and the mains put directly on to the running coils, which are indicated by the heavy spirals *c c* in the motor M, but also at the same time the starting coils *s s* of the motor are taken out of circuit, and cease to draw current from the mains. The actual apparatus, with its three-armed switch S_3 and the auxiliary switch S_2 and its contacts, is shown in Fig. 808, which will be readily understood by reference to the diagram in Fig. 807.

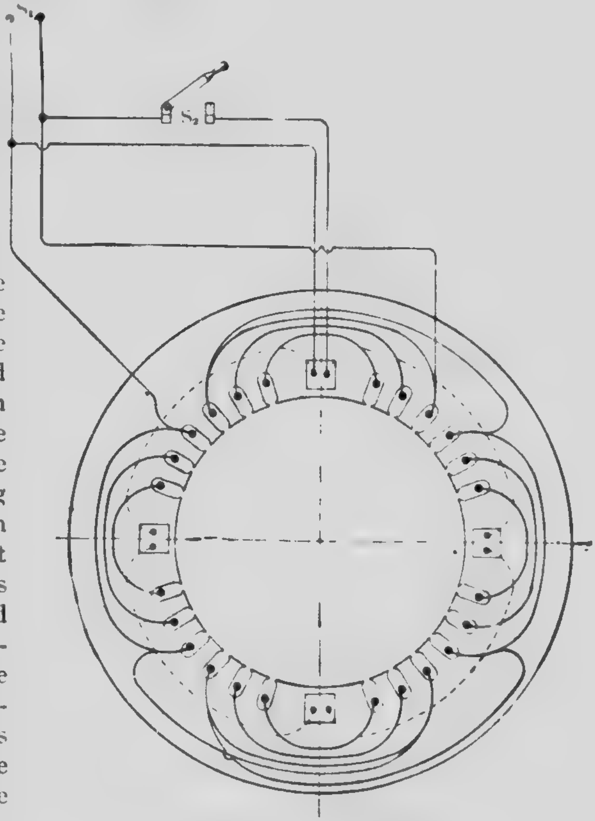

Fig. 806.—Stator Windings of Heyland Motor.

When the motor is required to start under load the resistance R is not required, and the mains are connected directly to the running coils *c c* of the stator. In this case the starting and auxiliary switch apparatus is somewhat simpler, the auxiliary switch having only one pair of contacts, in which it rests for starting purposes, closing the circuit of the starting coils. As the three-armed switch is moved over to the running position these contacts are opened, and the auxiliary switch arm rests against the stop shown on the left.

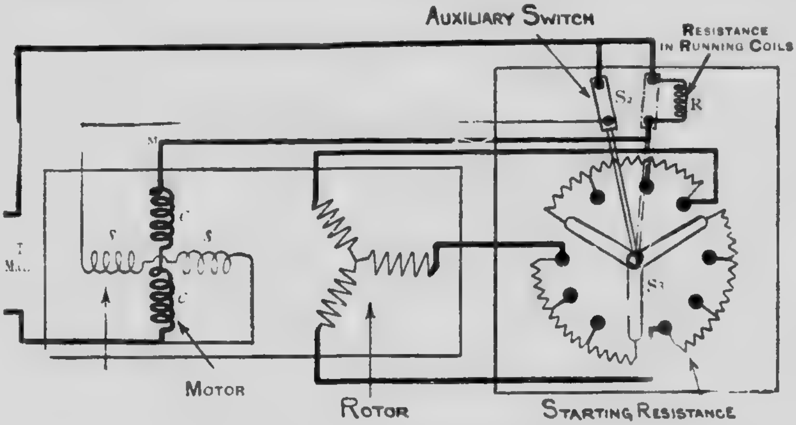

Fig. 807.—Starting Connections of Heyland Motor under "No Load."

For periodicities up to 60 the starting current is four-fifths of the full-load current for a light start and twice the full-load current for a loaded start. For higher periodicities the currents taken are somewhat greater. The motors are rated to run continuously with a rise of temperature not exceeding 50° C. for the smaller sizes up to 20 B.H.P., and a rise of 40° C. for the larger sizes. They can be overloaded 25 to 30 per cent. before pulling up. When the load torque exceeds what the motor can develop the motor does not slow down and run at a lower speed, but gets out of step and stops dead, and the proper starting operations have to be used to get it running again.

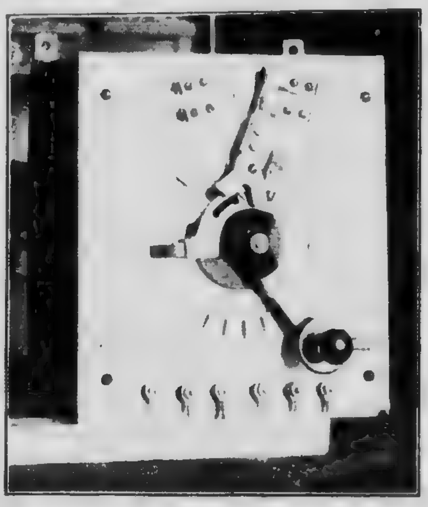

Fig. 808.—Switch for Starting Unloaded Motor.

The Heyland motors are built in standard sizes, from $\frac{1}{2}$ to 100 B.H.P., at speeds depending on the periodicity of the supply circuit. With currents at 50 ∿ the speed varies from 1,400 to 585 R.P.M. The full-load efficiency varies from

0 per cent. for the 2-B.H.P. size to 89 per cent. for the 100 B.H.P., the orresponding power factors being 0·72 and 0·79 respectively at full load; hese figures are for periodicities from 40 to 60 ∾.

The Langdon-Davies Motor.—One of the earliest successful pioneers n this field, and one which has been improved from time to time nd is very widely used, is the Langdon-Davies motor, manufactured y the Langdon-Davies Motor Company, of London. The motor itself

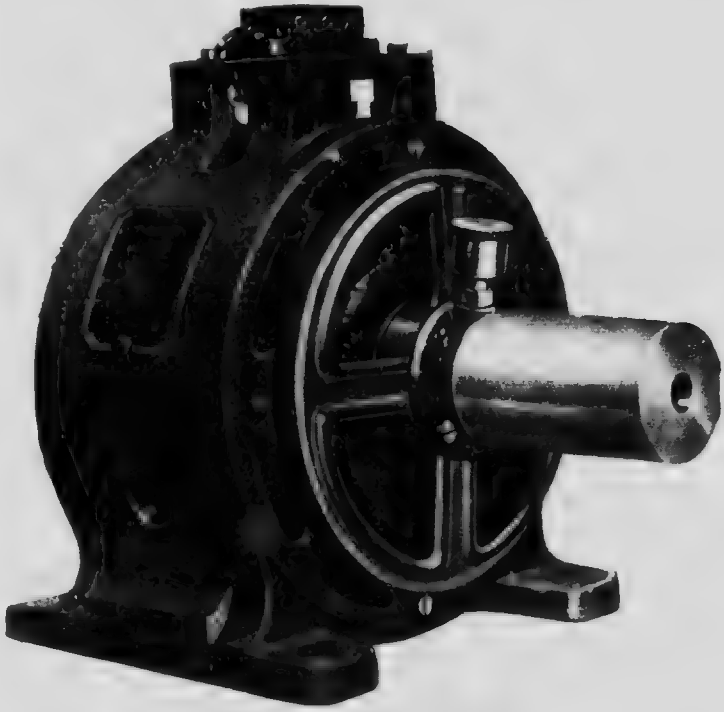

Fig. 809.—The Langdon-Davies Motor.

is illustrated in Fig. 809; like most indu[illegible] motors, with short-circuited rotors it exposes no working parts, [illegible] the only mechanical friction is that of the bearings, which in the size selected for the illustration are carried by brackets bolted to the sides of the machine. Although the motor is to be supplied with monophase currents, there are three terminals, the extra one being used for starting purposes only. The stator and the rotor are shown separately in Figs. 810 and 812 respectively. The machine is a four-pole machine, and the stator (Fig. 810) is wound with eight coils, four of which are the "running" coils and four the "starting" coils. The running coils are the inner ones *a*, and when excited will give a four-pole magnetic field, with the lines of the poles inclined at 45° to the vertical; they are so wound that the field produced is fairly evenly distributed over the polar faces, which in this case consist of nearly one half of the inner cylindric surface. How this is accomplished can best be followed by reference to the stator stamping, one half of which is shown in Fig. 811, from which it will be seen that the coils are wound in deep tunnels, roughly 1¼ inches long by ⅜ inch wide. There are thirty-two such tunnels, which gives eight to each pole. In some more recent machines, as shown in Fig. 810, the tunnels have been opened up by very narrow slots, 0·06 inch wide on the face of the stator. The winding is spiral; starting in slots 8 and 9, it then passes to slots 7 and 10, then to 6 and 11, and so on until it finishes in slots 5 and 12. Now, the reluctance of the path of the lines which have to travel from between slots 8 and 9 to the part of the rotor just below slot 1 and back through the yoke is greater than the reluctance of the path of the lines which only travel from the neighbourhood of slot 5 to the corresponding slot 4 immediately below it and back again. For an equal flux the former lines therefore require a greater magnetomotive force than the latter, and this is obtained by winding more turns in slots 8 and 9 than in the other pairs of slots, and gradually reducing the number of turns in each pair until the minimum is reached in slots 5 and 12. The result is a field which is almost, but not quite, uniformly distributed, the disturbing elements being the presence of the slots and the partial localising of the windings. Also the teeth of the rotor produce a certain amount of fringing of the field, which will be referred to later.

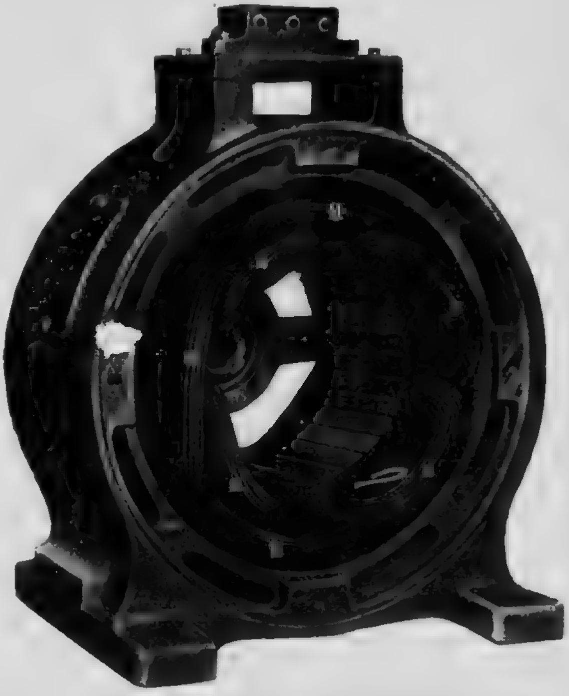

Fig. 810.—Stator (Wound) of Langdon-Davies Motor.

Turning now to the rotor (Fig. 812), it will be noticed that the grooves or slots in which the conductors are wound are staggered—that is, they do not run parallel to the axis of the rotor, but make a more or less acute angle with it. This device is adopted because of the fringing of the stator field referred to above, and the result is that the conductors in each slot at a given instant are partly in a fringed or dense field, and partly in a weaker one. Thus the average field per conductor and the consequent E.M.F. induced are fairly uniform right round the rotor, giving a much more uniform torque than would result if some of the conductors were in denser and others in weaker fields. The core of the rotor consists of wide teeth, with narrow, straight slots, as shown in Fig. 813, which depicts one half of one of the stampings. The width of the teeth is more than three times the width of the slots, and there are forty-seven of each. As there are thirty-two tunnels, or slots, in the stator, the ratio 32 to 47 between the two numbers is an incommensurable one, thus following the rule already discussed with reference to polyphase motors. The reasons for the rule are stronger with the fixed stator fields of monophase motors than with the rotating fields of polyphase machines, for the tendency to act as a static transformer without developing a torque is obviously much

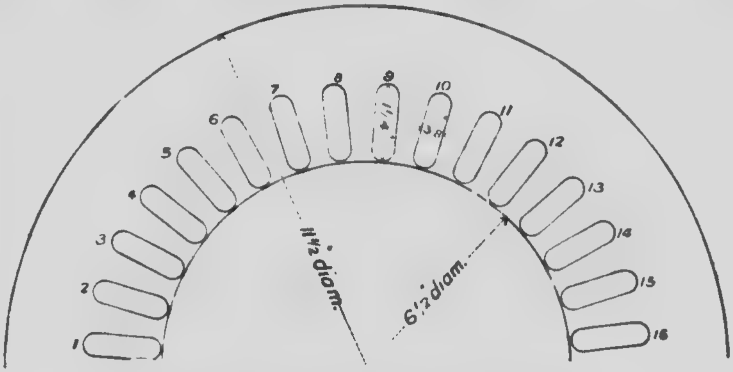

Fig. 811.—Stator Stamping of Monophase Motor.

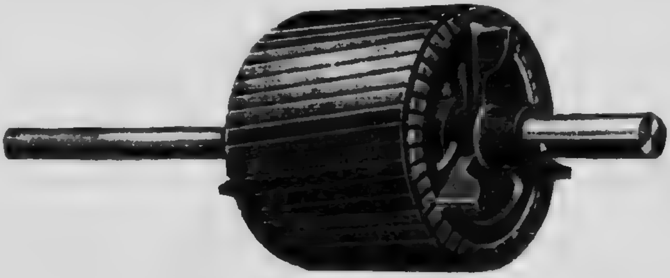

Fig. 812.—Rotor of Langdon-Davies Motor.

greater in the former case than in the latter.

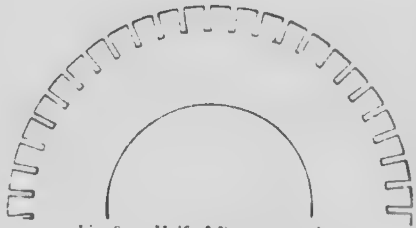

Fig. 813—Half of Rotor Stamping.

The core discs (*see* Fig. 813) drive a three-armed spider keyed to the shaft, and there is ample ventilation space between the shaft and the coils. The spider also carries lugs, which act as fans for driving air through the rotor. The conductors consist of bare copper bars driven into the slots cut in the rotor iron. The ends of these bars are hard-soldered to heavy gun-metal rings at each end, thus forming the squirrel-cage type of rotor.

An interesting detail of construction is shown in Fig. 814, which gives particulars of the yoke ring Y and the method of fixing the stator stampings therein. These stampings s, with thickened end plates *r*, are assembled in a suitable jig with the cast-iron yoke ring in the position shown. An additional smaller ring A with a groove *g* on its outer surface, corresponding to a similar groove *f* on the inner surface of the yoke ring, is then fixed in position and molten type metal is run into the space shown black in the figure. This type metal expands in solidifying, and effectually keys the whole together in a firm mass.

It remains now to describe the details of the method of *starting* these motors. As already explained, the starting coils are the outer coils *b* seen in Fig. 810. They are wound in the same slots as and below the running coils; but their axis is at 45° to that of the latter, and therefore alone they would produce a field at 45° to the running field. When starting, the two sets of windings are connected in parallel, and are arranged to give the same number of ampere turns; therefore, if supplied with currents in the same phase they would produce a four-fold field fixed in space with the centres of the

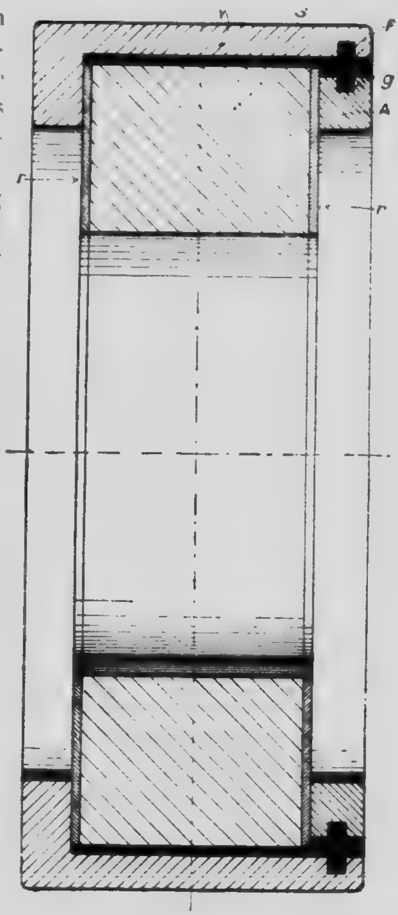

Fig. 814.—Construction of Stator Carcass.

polar areas, about 22½° from the horizontal and vertical sections of the tator. This is avoided by introducing an extra resistance into the circuit of the running coils, and thus altering the ratio of L to R, which changes the angle of lag (*see* page 543, Vol. I.), and throws the currents in the two windings out of step. The result is to give a rotating field. It was remarked at page 626, Vol. I., that the rotation of a field so produced will not, as a rule, be uniform, but will be "more or less

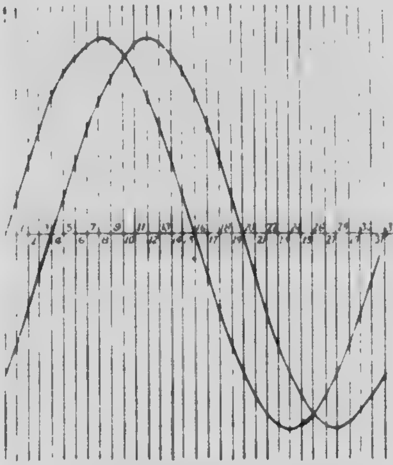

Fig. 815.—Sinusoidal Currents, Phase Difference ¼th Period.

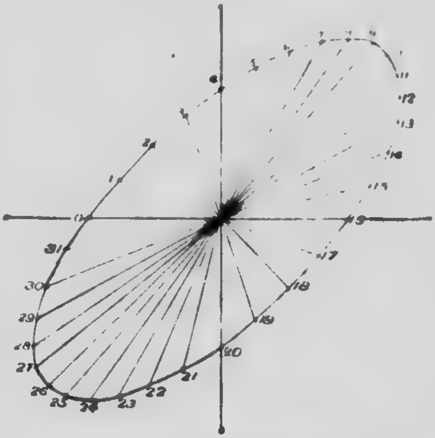

Fig. 816.—Rotating Two-pole Field given by Currents in Fig. 815 Axes 90° apart.

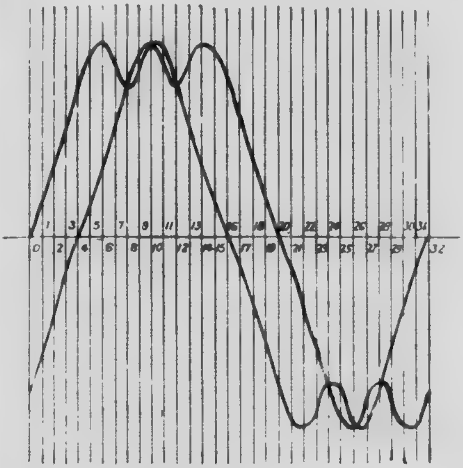

Fig. 817.—Similar Peaked Currents, Phase Difference ¼th Period.

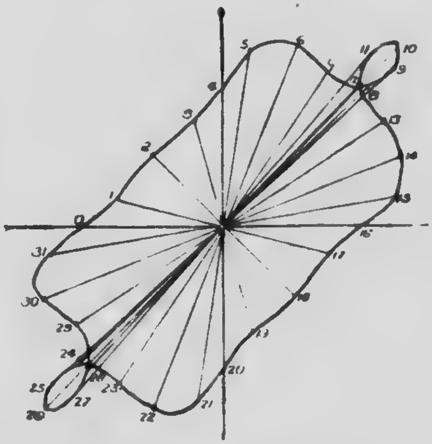

Fig. 818.—Rotating Two-pole Field given by Currents in Fig. 817 Axes 90° apart.

jerky." In the present case, to obtain uniform rotation the two currents should be in quadrature—that is, one should lag a quarter of a period behind the other. But this requires that the ratio of p L to R should be very great, and by splitting the phase as above it is seldom possible in practice to obtain a lag greater than one-eighth of a period. The result when the supply current is sinusoidal is shown for a two-pole field in Figs. 815 and 816.* Fig. 815 shows two such equal currents placed as in the stator, but with one lagging one-eighth of a period behind the other. The resultant field produced with a two-pole winding is shown in magnitude and direction for the different instants of time marked on Fig. 815 by the length and position of the radial lines in Fig. 816. It will be noticed that in the first eighth of a period a somewhat weak field sweeps round a quarter of a revolution, whilst it takes three times as long to sweep round the next quarter with a much stronger field. The field therefore varies during a single revolution, not only in speed of rotation, but also in intensity. This is with sinusoidal currents, but the influence of waveform is very important in this matter, and with more complicated currents the effect is much worse, as shown in Figs. 817 and 818. In Fig.

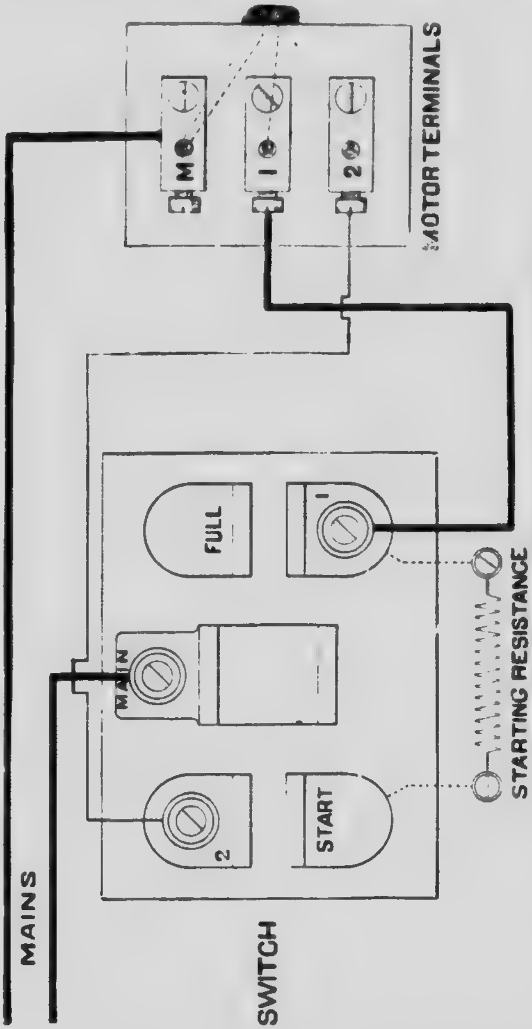

Fig. 819.—Connections of Starting Switch of Langdon-Davies Monophase Motor.

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* For Figs 815 to 818 the author is indebted to Mr. Langdon-Davies.

17 the two currents, still displaced an eighth of a period on one another, ve each two peaks. The effect on the resultant rotating field (Fig. 18) is very curious. The whole period being again divided into thirty-wo equal intervals of time, during the first four of these, from 0 to 4, the eld moves round a quarter of a revolution; and in the next twelve, om 4 to 16, through the next quarter of a revolution. But during part of this time, namely from 9 to 11, the field rotates backward, nd the motor will act as a generator if the rotor, as it must owing its inertia, continues to move forward in its original direction. In s case the motor could not run up to the synchronous speed.

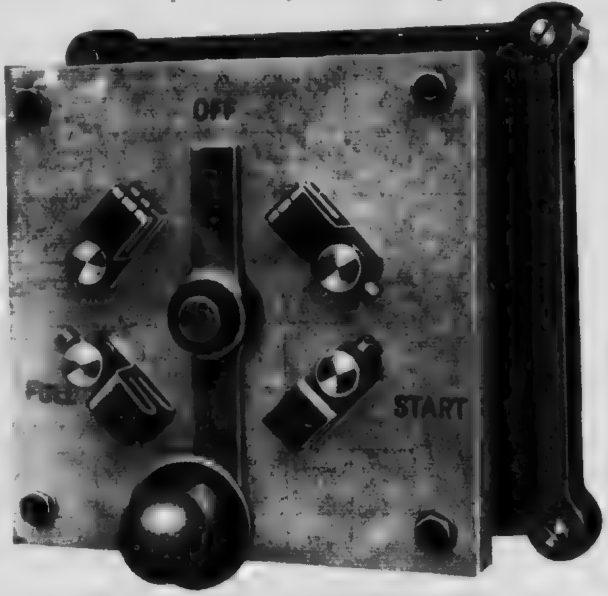

Fig. 820.—Starting Switch and Resistance (*see* Fig. 819).

It follows from the ove that to obtain e requisite rotating ld, to ensure a good rt by splitting the ase, is by no means easy a matter as might appear at first sight, and that great care must be exercised in designing and placing the auxiliary or starting winding used for this purpose.

The connections of the switch used for the purpose are shown in Fig. 819, in which the motor terminals are marked M, 1 and 2. Of these M and 1 are the terminals of the running coils of the stator and M and 2 the terminals of the starting or auxiliary coils. When the switch is thrown over to the left the block marked "Main" is connected to the block marked "Start," and these two sets of coils are connected in parallel across the mains, but an external starting resistance is in series with the running coils. This gives the necessary phase difference, and the motor starts as a polyphase induction motor. When the speed has run up nearly to synchronism the switch is thrown over quickly to the right, putting the auxiliary coils out of circuit and leaving the running coils alone and without external resistance on the mains. The actual switch with the necessary resistance in the space behind is shown in Fig. 820; it is mounted on a non-inflammable base, and since the resistance has to carry current only during the starting period, it may be allowed to become fairly warm without impairing its usefulness. It is, however, well exposed to the air, and rapidly loses the heat generated.

It is claimed for these motors that the starting current is not greater than the full-load current, and that the power factor is high. They are made in sizes from ½ to 35 B.H.P., the speed depending on the periodicity. The results of the tests of a 4-B.H.P. motor are given in Fig. 821, from which it will be seen that at full load the power factor is 0·70, and that from half to full load the efficiency varies from 72 to nearly 76 per cent.

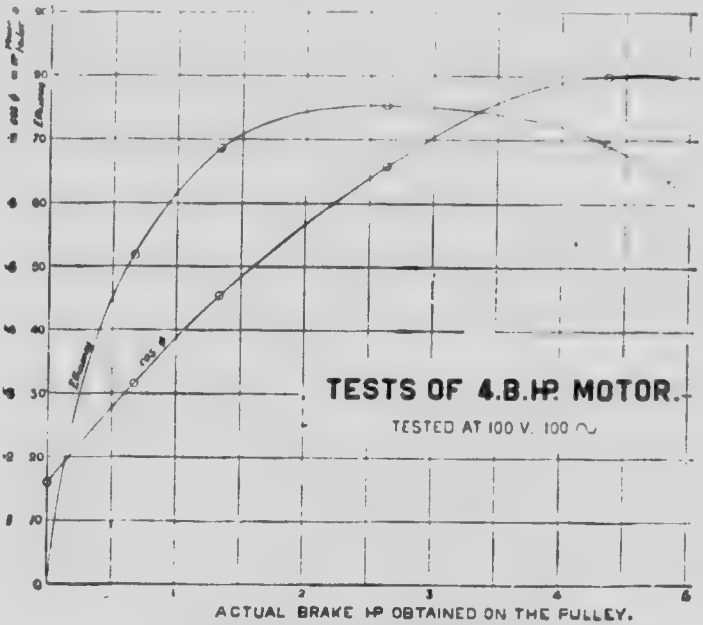

Fig. 821.—Tests of a Langdon-Davies Monophase Motor.

There are, of course, no rubbing contacts, and the machine is sparkless, all circuits being closed. The motors are not intended to start under load, as the torque developed by the starting arrangement is not great.

VII.—MONOPHASE COMMUTATOR TRACTION MOTORS

There are many applications of alternate currents, but more especially in electric traction, in which the requirements make it very desirable that there should be available monophase motors which, like continuous-current motors, can start under full load and run with good efficiencies at all speeds from slow up to the full speed for which they are designed. The requirements referred to will be dealt with in a subsequent section, but it y be stated briefly here that although for traction conditions the con-nuous-current traction motor fulfils many of the practical requirements mirably, and as a motor has a fairly high efficiency even at low speeds (Figs. 647 to 649), this efficiency can only be obtained in practice by tting down the voltage at the motor by means of wasteful resistances, that the over-all efficiency taken between the supply conductors somes falls as low as 30 per cent. under starting conditions. Moreover, ing to difficulties of commutation, continuous-current traction motors nning at much higher pressures than 1,500 volts have not been found nerally practicable.

On the other hand, the polyphase induction motor, though able to high voltages and to start under full load with more economy, has

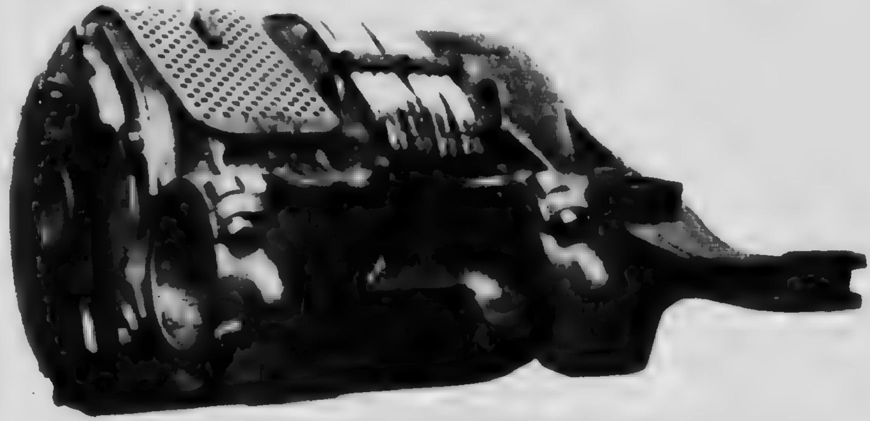

Fig. 822.—Westinghouse 150 H.P. Monophase Commutator Traction Motor.

limited range of working speed, even when two are placed in "cascade," as explained above. In addition, it requires in traction work three conductors under the most favourable conditions, and therefore at least two f these must be insulated and energy taken from them by overhead or other connections. Thus complications are introduced into the switching and controlling arrangements which increase the risk of breakdown and also add to the initial cost.

In the following pages some single-phase traction motors of the commutator type and some of the methods of working and controlling them are first described. In the next section reference is made briefly and from an elementary standpoint to some of the difficulties, both theoretical and practical, which present themselves in this solution of the general problem.

The Westinghouse Commutator Motor.—The external appearance of a single-phase traction motor as built by the Westinghouse Electric and Manufacturing Company is shown in Fig. 822. This motor is rated at

150 B.H.P., is designed to run on a circuit of 15 or 25 cycles, and is wound for a pressure of between 200 and 350 volts. It somewhat resembles in external appearance the continuous-current traction motors already described and is designed like them for single-reduction gear. The complete armature is illustrated in Fig. 823, and differs little in external appearance from a continuous-current armature of the traction type; there are the usual ventilating ducts, and the slots are rectangular in section, the winding being of copper strap, held in place by wedges of hard fibre or compressed paper, binding wires being used only for holding down the end connections.

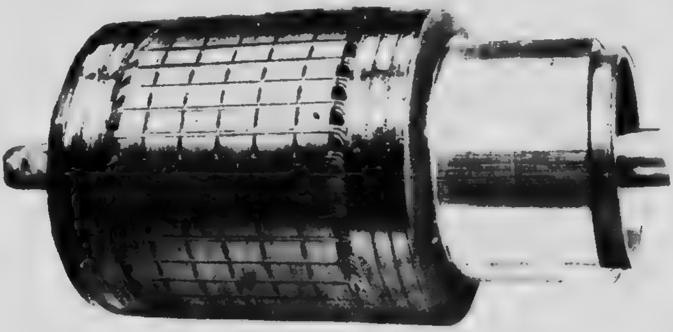

Fig. 823.—Armature of Westinghouse Commutator Motor.

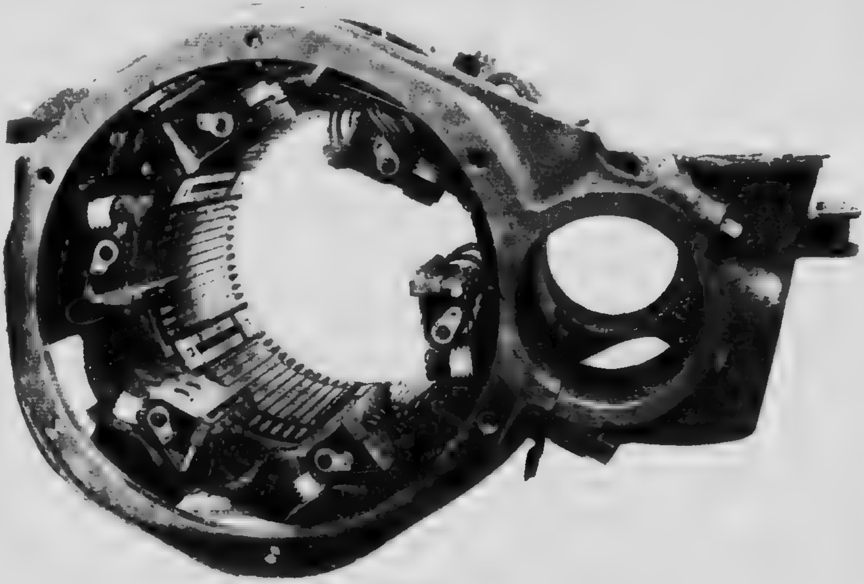

Fig. 824.—Stator of Westinghouse Commutator Motor.

Fig. 824 is an illustration of the motor stator without the two end brackets, and shows in the foreground the arrangement and position of the brush-holders. Behind these the laminated poles with their series and mpensating windings can easily be seen. Fig. 825 gives a detailed ew of a type of brush-holder which is generally employed with this type motor. The carbon brushes are carried in cast brass holders, with slots vided for the brushes and with springs for pressing the brushes against commutator surface. Most of the details of the motor resemble those continuous-current railway motors, and attention need only be directed a few special modifications.

In the first place the field magnets are made up of laminated steel mpings, which are removable in the same way as the stator of an luction motor, except that the field is made up of six distinct poles. The ter frame is of cast iron, and does not form part of the magnetic circuit. It need therefore only be constructed with the view to mechanical strength.

As shown in Fig. 824, the winding of the field consists of two entirely independent sets of coils: the main field coil for producing the effective magnetic field, and the auxiliary or compensating winding for counteracting the armature reaction. The main field winding is made up of coils of several turns of strap copper, and is placed over the poles in such a manner that it is possible to remove the coil without disturbing the auxiliary winding. The auxiliary or compensating winding is a distributed winding, being carried in slots which are distributed over the pole faces. This winding is generally made of copper bars, which are pushed through the pole slots and connected at the ends with strap connectors.

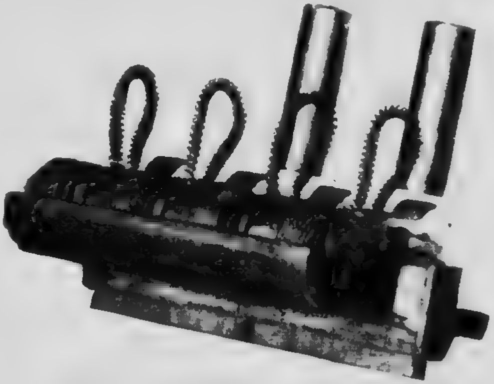

Fig. 825.—Brush-holder of Westinghouse Commutator Motor.

Part of the armature winding is shown developed in Fig. 826. This winding is a single closed-circuit lap winding with one complete turn bridging each commutator gap. The conductors are straps of copper placed side by side in the slots, each coil spanning a given number of armature teeth according to the number of slots provided in the armature.

The performance curves of this motor, when running on a circuit of 25 cycles and at the pressure of 235 volts, are shown in Fig. 827, in which the tractive effort, the B.H.P., the speed, the efficiency, and the power factor are plotted against the current. Attention should be directed to the large tractive effort at low speeds, the speeds plotted being those of a car with 42-inch wheels geared to the armature with a mechanical gear reduction of 76 to 23, which means that the pinion of the motor is provided with 23 teeth, while the gear wheel which is keyed to the coac axle is provided with 76 teeth. The efficiencies are plotted with an without the losses of this reduction gear.

The general demand for a motor which will give a maximum H.I output at a minimum weight and expenditure of material has led, in th case of traction motors as in the cases of other motors (*see* pages 618 an 619), to the introduction of the ventilated motor, and this means of increasing the capacity of railway motors in general has now been adopted b most of the leading manufacturers. Two distinct methods of ventilatio have so far been designed and are in general use: "self-ventilation" an "forced ventilation." On the self-ventilation system, the armature i provided with a fan at the end opposite the commutator. The air is drawn from outside through an opening in the frame, and passes over the armature surface and between the field coils, passes over the commutator, and returns through the spider web and through the ventilator out into the open air. A motor provided with this type of ventilation can be rated higher than an unventilated motor, and it is generally assumed that the continuous output of the motor can be increased by 30 per cent. This means of ventilation is largely adopted for passenger motor cars.

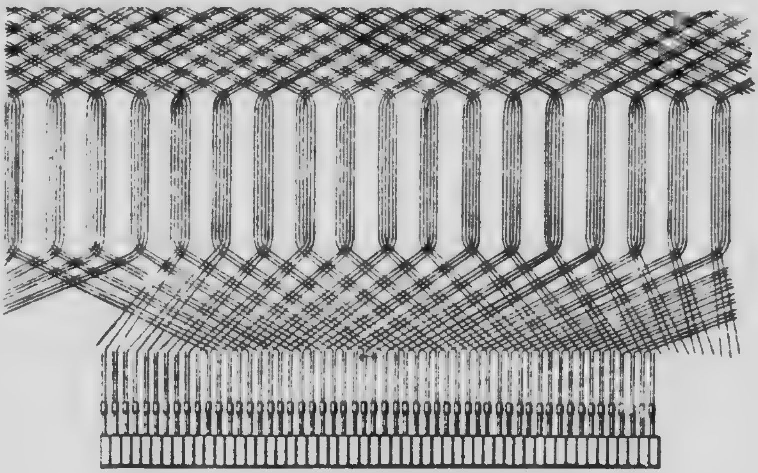

FIG. 82[illegible].—Developed Winding of Commutator Traction Motor.

On the forced ventilation system the motor is built like a totally enclosed motor, but openings are provided in the field frame at both ends of the motor, and by means of an external fan air is blown in at the commutator end of the motor and exhausted at the opposite end. By this means the capacity of the motor can be increased to as much as 80 per cent. above it of totally enclosed machines by adjusting the quantity of air blown rough the motor.

The Winter-Eichberg Commutator Motor.—This traction motor of interest to Londoners, as it was the motor adopted by the London, Brighton and South Coast Railway Company for the electrification in 1909 its South London lines, as described elsewhere (pages 1540 and later). The

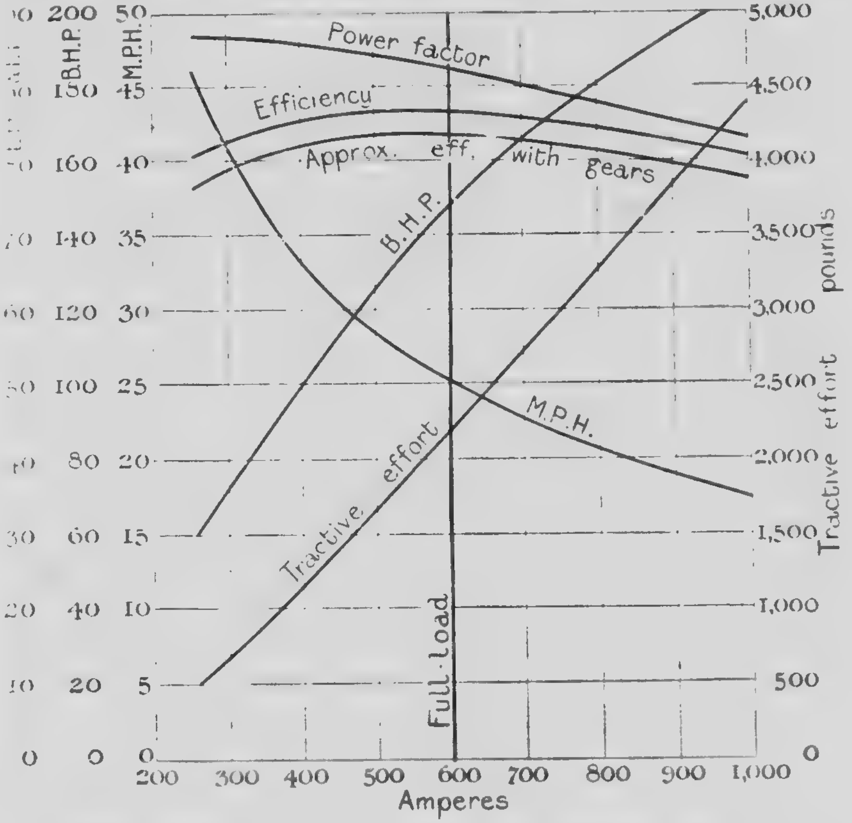

Fig. 27.—Performance Curves of the Westinghouse 150 H.P. Motor [illegible] Commutator Motor

connections of the motor are generally as just described, but the full line voltage of 6,000 volts was stepped down by transformers to a maximum of 750 volts for the stator circuits, a lower voltage being supplied to the rotor to ease the commutator difficulties.

The motors were 115 H.P. four-pole motors, which at the supply periodicity of 25 cycles gave a synchronous speed of 750 R.P.M. The speed of the armature was stepped down by single reduction gearing in the ratio of 4·24 to 1, and as the driving wheels were 43·5 inches in diameter the speed of the train in miles per hour was got very nearly by dividing the speed of the armature in R.P.M. by 33. Thus the speed of the train corresponding to the synchronous speed of 750 R.P.M. was just under 23 miles per hour As the trains could be run at over 40 miles per hour (*see* Fig. 830), the independence of the synchronous speed in the case of the commutator repulsion motor is amply demonstrated.

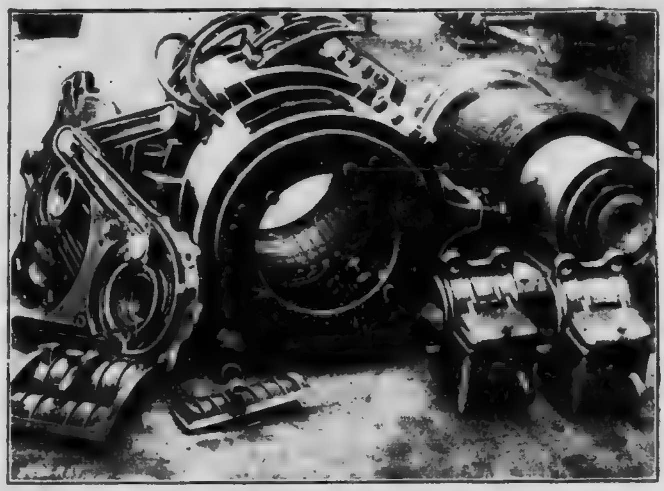

Fig. 828.—Traction Motor on the L. B. & S. C. Railway.

One of the motors is shown dismantled in Fig. 828. The stator has six slots per pole, which are not uniformly distributed but are collected at the polar horns, and there are also two compensating or commutating coils. There are two sets of brushes only for the ordinary armature current, as is usual with four-pole continuous-current traction motors, but

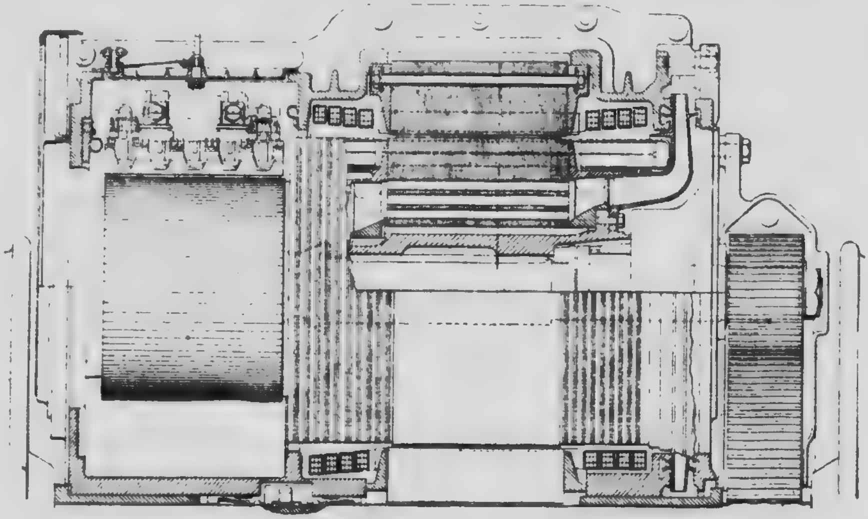

Fig. [illegible].—Part Section of an A.C. Traction Motor.

n addition there are four sets of short-circuited brushes placed electrically pposite the middle of the pole faces for dealing with the transformer tion of the stator flux and acting as the brushes *a*, *b* in Fig. 835. urther details of the armature and the stator are given in Fig. 829,* which a drawing giving a longitudinal part section of the motor, including some details of the magnetic circuit and of the brush gear. The air ıp is 3 mm. The shaft is partly hollow, air being drawn through the mature partly by centrifugal and partly by fan action. As explained lsewhere, larger motors ave been installed in ne more recent extensions of the system.

In the method of ntrol adopted on the outh London line, comnations of contactors re used which give five positions for the master ontroller, and the perormance of the motor or the voltage supplied rom each of these five positions is shown in Fig. 830, which is selfxplanatory and worthy of careful study in connection with this type of motor. These curves should be compared with the corresponding curves for other motors, monophase and polyphase, as well as with curves for continuous-current traction motors. Further references to the method of control will be found in Chapter XVII., *infra*.

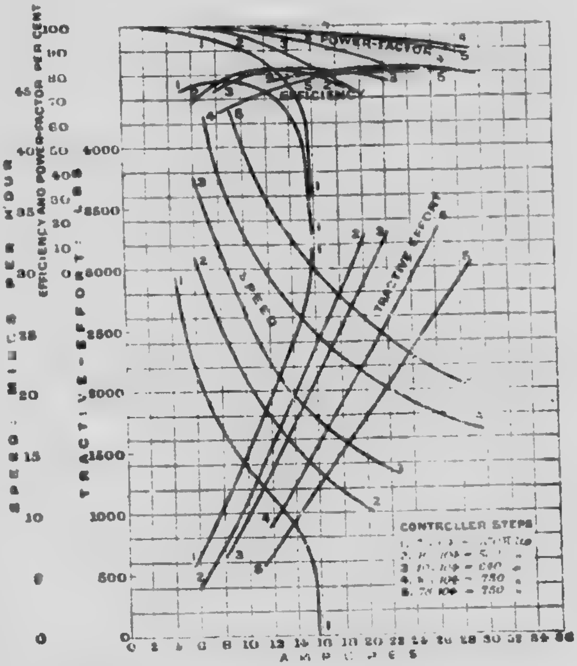

Fig. 830.—Performance Curves of Traction Motor on the L. B. & S. C. Railway.

The Oerlikon Commutator Motor.—The locomotives built for the Lötschberg (Swiss) Railway by the well-known Swiss manufacturers, the Maschinenfabrik Oerlikon of Zurich, are particularly interesting in this connection. They are actuated by large single-phase motors of the compensated-series type, and, as will appear from Fig. 831, much more closely resemble ordinary large continuous-current dynamos and motors than is usual even in continuous current traction work. The earliest of these locomotives was built as an experimental machine in 1908, and after exhaustive trials was adopted in 1911 for the railway which was then under construction. The line was opened in June, 1913, and will, with further details of the locomotives, be referred to later. At present we are concerned with the motors only.

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* From a paper by Mr. Philip Dawson in *Proc. Inst. Civil Engineers*, Vol. CLXXXVI. 1911).

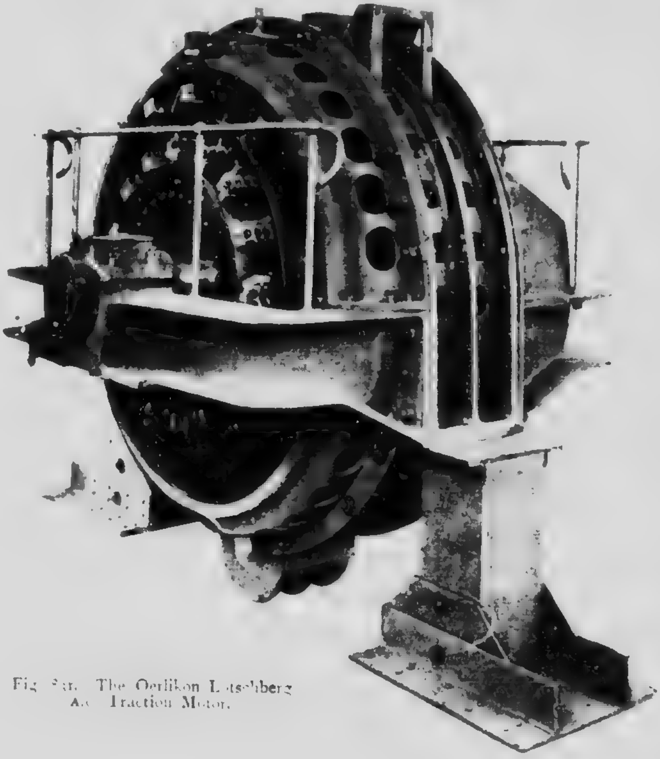

Fig. 831. The Oerlikon Lötschberg A.C. Traction Motor.

In addition to the view of the complete motor given on Fig. 831, the stator (field magnet) and rotor (armature) are shown separately in Figs. 832 and 833. The motor is designed for an output of 1,250 H.P., and must maintain this output for one hour and a half without overheating; with its gearing it weighs 14 tons. The maximum pressure is 500 volts, and for the maximum power the current is about 2,000 amperes. The stator or field magnet has sixteen poles and sixteen interpoles; the pole faces can be clearly seen in Fig. 832, and also the end connections of the exciting coils; the coils for the compensating poles are wound in slots on the surface of the main pole faces, and the main exciting coils, with their axes displaced 90 electrical degrees, lie behind them. Between the stator and the rotor the air gap is only 3 mm. wide, a very small clearance in a multipolar motor of this size to be used for traction work.

The armature, or rotor, is shown in Fig. 833, which is a view from the driving end, and shows the pinion of the toothed gearing which is contained in a housing, part of which can be seen on the far side in Fig. 831; the speed reduction is 2·23 to 1, and one of the bearings for the axle of the r wheel can be seen mounted on the bottom of the casing of the motor. he rotor winding is secured by slot wedges and binding wires, and at e normal speed : the locomo-ive, 50 kilo-etres per hour, e rotor runs at speed of about 50 R.P.M., hich, since the equency of the upply is 15 eriods per second, is about ur times the ynchronous speed of an induction motor with the same number of poles.

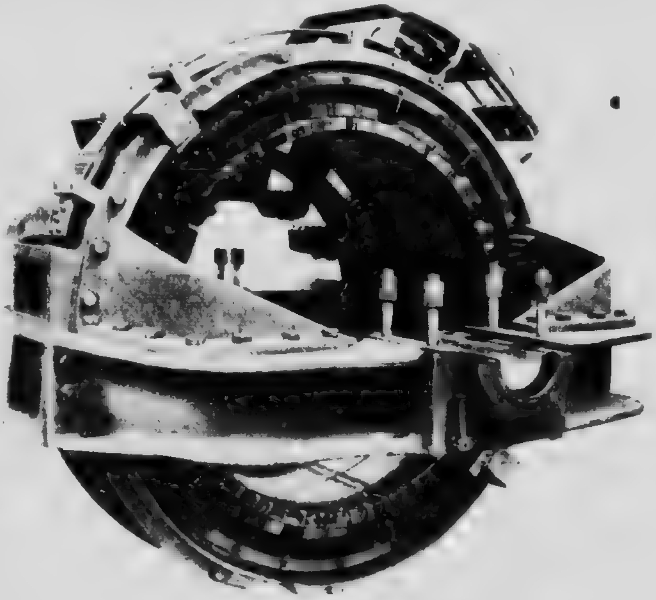

Fig. [illegible]—Stator of the Oerlikon A.C. Traction Motor.

The performance curves of the motor for different voltages at its terminals are given in Fig. 834, in which, plotted against the current as a base, will be found the power factor (Cos ϕ), the efficiency (η), the output (L) in horse-power, the draw-bar pull (Z) in kilogrammes, and the speed (v) of the train in kilometres per hour. If there be no slip at the wheels the speed of the motors in R.P.M. is about nine times the speed of the train in kilometres per hour. The actual locomotives and the methods of controlling the speed are dealt with in the section on railway traction

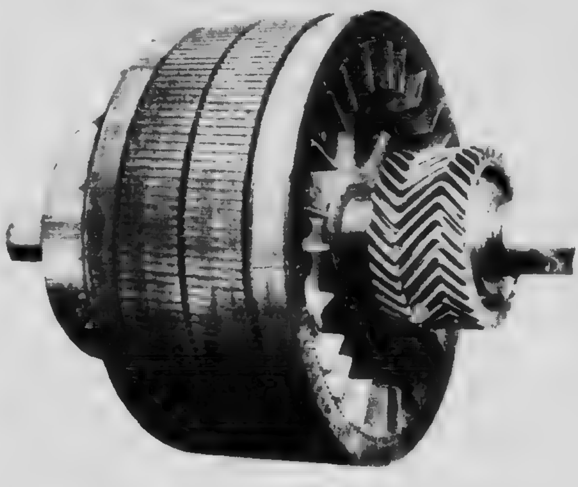

Fig. 833.—Rotor of the Oerlikon A.C. Traction Motor.

VIII.—NOTES ON THE ELEMENTARY THEORY AND WORKING OF THE ALTERNATE-CURRENT COMMUTATOR TRACTION MOTOR

The general considerations which have led to the development of the alternate-current commutator motor have been referred to in the preceding pages, and incidentally, in the description of machines, some of the inherent difficulties and their solutions have presented themselves. The following brief remarks deal more systematically with these difficulties and solutions.

The main practical problem is that of producing an A.C. motor which shall have a speed-torque characteristic similar to that of the C.C. series motor which has been found so useful in traction and other work. This problem is not quite the same with monophase as it is with polyphase currents. If the latter are supplied to a properly wound stator they produce quite easily and naturally a rotating field. A monophase current, on the other hand, produces a field fixed in space and simply alternating in time, unless some such device as splitting the phase, which is fully described in other parts of the book, be adopted, and except so far as a rotating field may be produced by the magnetic reaction of the armature. The phase-splitting devices, though useful for starting, are not economical or desirable for long-continued runs on load. Fortunately, the simple solution of bringing back the commutator into A.C. work, though beset with certain difficulties, has been found to be both practicable and convenient. The principles of the solution, however, are somewhat different from those which lead to the use of a commutator on polyphase motors.

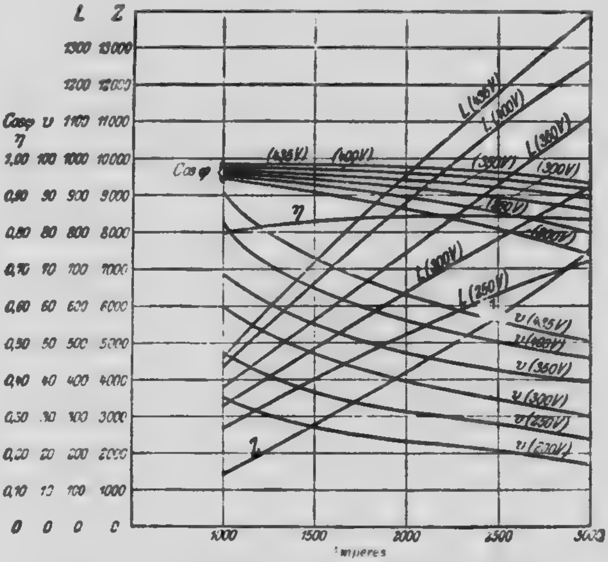

Fig. 834.—Performance Curves of the Oerlikon Traction Motor.

It has already been pointed out (*see* page 607, Vol. I.) that a series-wound, continuous-current motor can be run with monophase alternate currents, and an early form of such a motor (Fig. 576, Vol. I.) has been described. If certain initial difficulties—to which reference will be made presently—can be overcome, such a motor would offer considerable advantages in comparison with either continuous current or induction motors. As compared with the former, the starting voltages for low speeds could be obtained from high line voltages by static transformers (either auto-transformers, Fig. 738, or ordinary transformers), which do not use up energy in the wasteful way inseparable from dead resistance control; and as compared with induction motors they would have a range of working speeds under load which would be better than, or at least equivalent to, those of the ordinary series-wound continuous-current traction motor.

The chief difficulties which must be overcome in order to secure these and other advantages may be summarised as follows:

(i.) Excessive sparking on the commutator due to high inductances and phase complications.
(ii.) Low power factor, giving rise to heavy wattless or idle currents (*see* page 763).
(iii.) Excessive and unequal heating, the former leading to low efficiency.
(iv.) The limitations of pressure due to the use of a commutator.

Dealing first with the difficulties of commutation, it might be considered obvious that if a commutator and brush gear were designed to give sparkless commutation at full load with continuous currents, then there should be no difficulty when the current varies from full value to zero, and rises again to full value in the reverse direction. Such reasoning would be correct if only the armature current were changing and if the field flux were maintained unchanged—or, rather, if the variation of the field flux did not introduce another factor, namely, an inductive E.M.F. in the armature coils independent of and in addition to the E.M.F. due to the rotation of the coils in a magnetic field, as in a continuous-current generator or motor. In fact, a static transformer action is added to the ordinary dynamo-electric action. Thus, in the bipolar field of Fig. 835, if the magnetic lines flowing from right to left through the iron ring are changing in number, there will be an inductive E.M.F. set up in each of the coils encircling the ring, whether the latter be revolving or stationary. For simplicity consider them stationary, then the closed circuit winding acts as the secondary of a static transformer, or, rather, the upper and

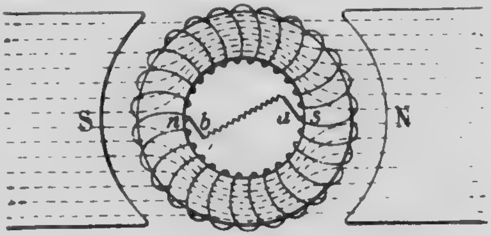

Fig. 835.—Transformer Action of Alternate Field.

lower halves act as two secondaries in parallel, the E.M.F.s in each half being added up and producing a P.D. between the points *a* and *b* on the horizontal diameter, between which, in an ordinary C.C. motor, there should be no P.D. If, then, these points be connected by a conductor —which can readily be done by placing a pair of short-circuiting brushes on the commutator—the inductive E.M.F.s will generate currents which, as usual in static transformers, will open up, by their magnetic reactions, the circuits of the primary or field-magnet coils, and thus raise the power factor of the whole combination. This device was used by Latour, Finzi, Winter-Eichberg, and others in early machines, and was [illegible]ed by placing two additional sets of brushes on the commutator 90° from the usual brushes, these auxiliary brushes being connected together. It is also the device used in "repulsion" motors. In considering the effects of these currents it must not be forgotten that there is a phase difference of a quarter period between the E.M.F.s thus induced in the armature coils and the varying field flux through the armature.

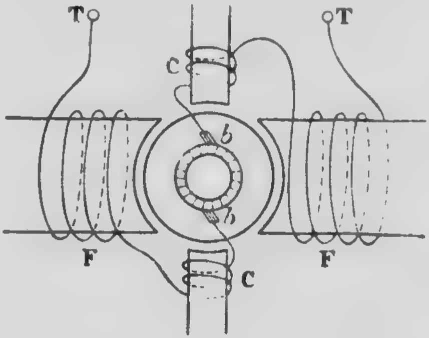

Fig. 836. The Series Commutator Bipolar Motor with Interpoles.

The addition of these transformer E.M.F.s and currents, as they may be termed, with their fluctuations and phase differences, to the E.M.F.s and currents of a continuous-current motor very much complicate the question of commutation, and make it impossible to find an entirely sparkless position for the usual brushes. Methods must therefore be adopted to diminish the evil. The simplest is to introduce resistances into the connections of the armature windings to the commutator, but without placing these connections on an active part of the armature, as in Sayers' method of commutating armature coils for continuous-current generators, described at page 124. This method has been elaborately worked out by Lamme and others, and was fully described in the last edition of this book. In addition, other devices, already described (*see* pages 103 to 129), for improving the conditions of commutation have been adopted, special account of course being taken of the changed conditions.

The greatest assistance—an assistance which is practically indispensable—is obtained from the use either directly or indirectly of the principle of interpoles, which has done so much to improve the commutation in continuous-current machines. It may be recalled (*see* page 107 *et seq.*) that this method acts by cancelling the cross-magnetising effect of the armature reaction, and the calculations of the designer are directed to neutralising exactly this effect by the series ampere-turns on the interpole. In the A.C. commutator motor the coils which carry these currents are usually referred to as the "compensating" coils. Their magnetic axis is, of course, at right angles to the field-flux axis shown in Fig. 835, and therefore roughly coincides in a two-pole machine with the line of the brushes through which external energy is being supplied to the armature. The connections are shown diagrammatically in Fig. 836; they are simply those of a continuous-current bipolar series motor with interpoles.

Alternate currents, however, are for this purpose, as well as for many others, much more flexible than continuous currents, because from their fluctuation they give rise to inductive E.M.F.s, an effect absent from the flow of steady continuous currents. It is therefore possible in this case to produce the compensating currents by electro-magnetic induction by simply short-circuiting the compensating coils and not connecting them to the external circuit at all, as shown in Fig. 837. By Lenz's law the induced currents in the compensating coils *c* will be in the required direction to tend to annul the flux in the brush axis which produces them. This method cannot, obviously, produce complete compensation, as some unbalanced flux must be left to produce the compensating currents; still further, it cannot give rise to over-compensation if that be required. The phase relations have also to be considered.

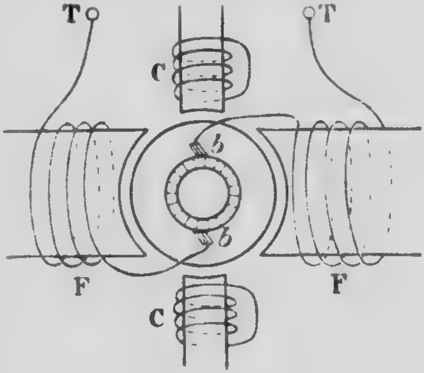

Fig. 837.—The Series Commutator Motor with Short-circuited Interpoles.

The Repulsion Motor.—Return now to the case of Fig. 835, with reference to which it was remarked that the device of short-circuited brushes was that employed in the "repulsion" motor, which it may be recalled was invented by Professor Elihu Thomson in the early days of electrical engineering developments (*see* page 625, Vol. I.), and which was a monophase machine. In the position given in Fig. 835 the armature would act as the short-circuited secondary of a static transformer, and if all the conditions, mechanical and electrical, were symmetrical, there would be no resultant torque tending to rotate the armature in one direction or the other. The symmetrical conditions would be upset if the armature were started rotating in either direction, or, better still, if the line of the brushes were moved from the horizontal diameter, as in Thomson's motor (Fig. 603, Vol. I.). The armature will then rotate with a more or less effective torque, according to the position of the brushes, and there will be superimposed upon the transformer E.M.F., (i.) the E.M.F.s due to the conductors cutting the magnetic flux, and (ii.) the armature reaction of the currents in the armature conductors which will not now lie in the direction of the field flux. We have the simplest form of the "repulsion" motor, for the magnetic effect between the poles of the armature and field will necessarily be one of repulsion.

By trial it would be possible to find the position of the brushes which gives the best effect for a particular load; but this position will not be one of sparkless commutation, since under the complex conditions set up such commutation is impossible. A considerable improvement will be obtained by placing the short-circuiting brushes on the diameter at right angles to the field and introducing the interpoles either in the main circuit, as in Fig. 838, or as in Fig. 839, the brushes in both cases being disconnected from the main circuit.

The first solution, however, namely that shown in Fig. 838, leaves the transformer effect, described on page 811, unbalanced, and therefore it is necessary to add the brushes along the diameter of the field flux, shown in Fig. 839, in which the central portion only of Fig. 838 is reproduced, the other connections being as in that figure. The brushes b_r b_r may be regarded as the repulsion brushes, and the brushes b_t b_t as the transformer brushes.

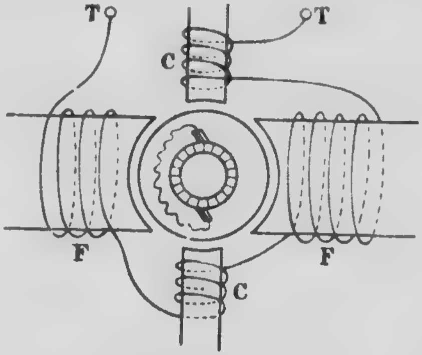

Fig. 838.—With Interpoles only.

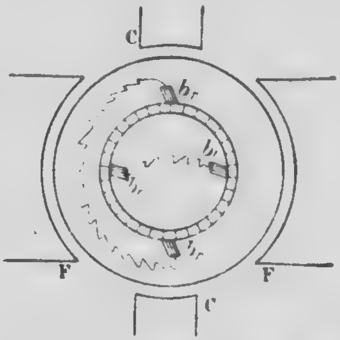

Fig. 839.—With Transformer Brushes added.

The Repulsion Motor.

With this development a new modification becomes possible, for it is obvious that if an external current be supplied to the brushes b_t b_t of Fig. 839, this current will produce a field in the same direction in space as the main field exciting current in any of the Figs. 835 to 839. It is therefore possible to dispense with the main exciting coils, and supply through these brushes a magnetising current to the armature, which being, in effect, a wattless current, will not absorb much energy. Being wattless, it must not be overlooked that it will be in quadrature with the alternate P.D. supplying it. The arrangement is shown in Fig. 840, in which only the cores C, which have been referred to hitherto as the compensating cores, are wound with excitation coils.

The above do not exhaust the possible arrangements, and the use of transformers brings still greater flexibility into the arrangements of any of the methods. The necessary currents for the rotor may obviously all be supplied from the secondary coil of a transformer. It is also possible to supply the stator currents direct from the high-voltage circuit and the rotor currents from a transformer. Or the different circuits, for instance F, C and H of Fig. 840, may be supplied from different tappings on the secondary of the same transformer. To exhibit this flexibility, the exciting current supplied to the armature brushes *b* in Fig. 840 is represented as being supplied from the low-voltage side of a current transformer D, the primary of which is in series with the compensating coils. This enables a high-voltage supply to be directly utilised without the necessity for employing a large step-down transformer, for the transformer D is quite small, as its only function is to supply a magnetising current.

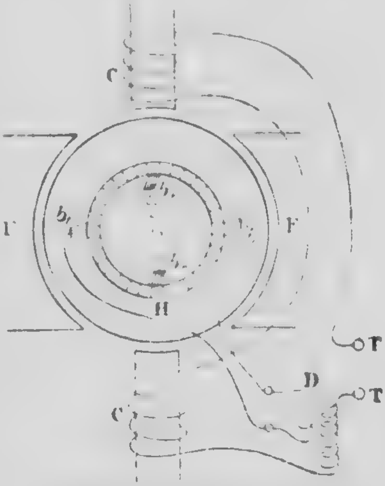

Fig. 840.—Repulsion Motor with Rotor Excitation.

But, whatever method is adopted, care must be taken by considering the chief functions of each circuit to ensure that the phase relations and currents supplied fulfil the conditions. The motors dealt with are all essentially series motors, and this fact must not be lost sight of if the principal object, namely a wide range of efficient speeds, is to be attained. The illustrations used (Figs. 835 to 840) are, of course, purely diagrammatic, and are not intended to indicate metrical relations. It would carry us much beyond the limits of this book to deal with these metrical relations which also include the phase relations.

Starting and Control.—As previously mentioned, it is one of the objections to this kind of motor that very high voltages cannot be used on a commutator, and that hence it cannot utilise all the advantages of a monophase supply. There are, however, as already pointed out, various ways of overcoming the difficulty, one of which is to work from the secondary of a transformer carried on the locomotive, though this, of course, introduces an additional complication and loss of energy. With such a device the controlling of single-phase motors for railway work is now generally designed on the multiple-unit system which allows of the control of almost any number of individual motor cars or motors operating in a train. With this system, which is described in the chapter on "Electric Traction," the motor circuit is not controlled directly by the driver, but by means of unit switches, which can be placed quite close to the motors and can be operated either electrically or pneumatically. The heavy current-carrying conductors can thus be made as short as possible. One advantage is that the controller, which is operated by the driver, only deals with the comparatively small currents necessary to excite the magnets of the switches, and can therefore be of small size, whether the motor be of 100 or 1,000 H.P. capacity.

The switches for the control of one motor group, consisting generally of two or four motors, are usually all mounted together on a frame, and form what is commonly known as a "switch group." If the locomotive of the motor car is fitted with two or more motors it is a common practice to connect them permanently in series, because in this case the voltage of the system can be doubled, and therefore the main switches can be built for a much lower current. The motors are connected through these switches to a number of tappings on the secondary of the transformer, by means of which variable voltage can be impressed upon the motors; and since the single-phase series motor has much the same characteristics as a continuous-current series motor (*see* Fig. 834), the speed of the car or train can thus be readily regulated. Fig. 841 shows diagrammatically the arrangement and sequence of the switches for a four-motor equipment as designed by the British Westinghouse Electric and Manufacturing Company. Each motor in this particular case has a capacity of 150 H.P., and the sequence of the closing of the different switches is shown in Fig. 842. In this table a black dot signifies that that particular switch is closed when the controller is on the step specified in the left-hand column. If the reader will compare Figs. 842 and 841, he will find that whenever a change is made to a new tap on the secondary, the resistance R is introduced, and that when the

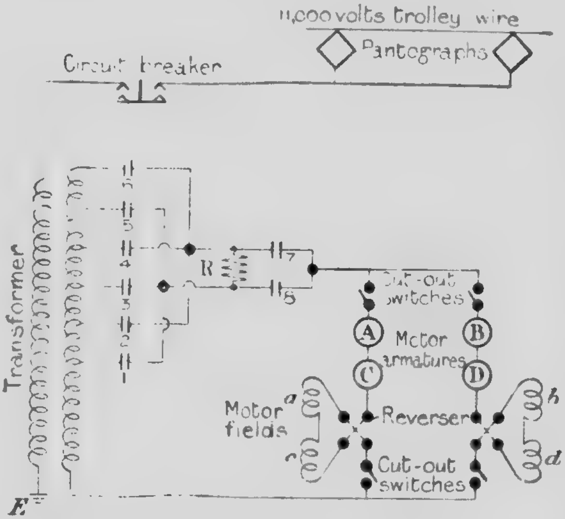

Fig. 841. Multiple Unit Control for Commutator A.C. Motors.

controller is moved to the next step R is cut out, whilst the connection to the secondary remains unchanged. In this way a better graduation of current and other advantages are obtained. In Fig. 841 the four motors are permanently connected, two in series and two parallel, the fields of each pair being directly in series, ensuring the same current through each. It should also be noted that reversal is accomplished by reversing the field current, and not by reversing the current in the armatures. The rest of the diagram (Fig. 841) is self-explanatory.

	Switch Numbers							
Step	1	2	3	4	5	6	7	8
1	●						●	
2	●							●
3		●						●
4		●					●	
5			●				●	
6			●					●
7				●				●
8				●			●	
9					●		●	
10					●			●
11						●		●
12						●	●	

Fig. 842.—Sequence of Switch Connections.

Another method of meeting the difficulty is to supply the high-voltage main current direct to the stator or field magnet only, thus saving the transformer losses on the portion of the energy drawn from this current; the armature current, however, must be passed through a transformer, because of commutator difficulties. Such a course was adopted with the early forms of the Winter-Eichberg commutator motor, the connections being as shown diagrammatically in Fig. 843. Starting from the lower main, the current first passes through the field-magnet coils from G to H, and then through the primary P of a transformer. The secondary S of this transformer is in sections, one or more of which can be connected to the reversing switch *x*, whence the current is passed to the brushes E and F. The rotation is reversed by throwing over the reversing switch, thus reversing the low-voltage armature current, and for starting purposes the voltage supplied to the brushes E F is lowered by using fewer of the sections of S, from which there are several tappings. Short-circuiting brushes for the inductive transformer currents in the armature windings are shown at *c* and *d*.

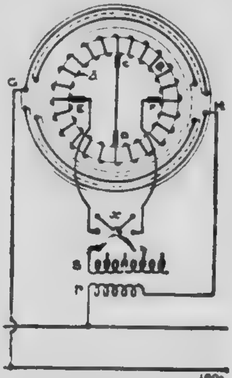

Fig. 843.—Starting and Controlling Connections for Early Form of the Winter-Eichberg Traction Motor.

The later Winter-Eichberg commutator motors, described above as used on the London Brighton and South Coast Railway, were carried in pairs upon the two bogies of a motor coach. One of these bogies, with its two motors, is shown in Fig. 844. Each pair of motors had its separate main transformer, the two motors being joined up permanently in parallel and operated by the same set of contactors, actuated by control circuits from a master controller either on the coach or on another motor coach on the train. The control currents were obtained from a small auxiliary transformer, whose primary was on a separate 6,600-volt circuit and in parallel with the main transformers. The pressure on the control circuits which run through all the motor coaches on the train was 300 volts. The electrical positions of the contactors in the power circuits was as given diagrammatically in Fig. 845. There were five taps on the secondary of the main transformer dividing it into four sections, giving 450, 580, 640, and 750 volts respectively. The currents for the armature were supplied from an auto-transformer, part of which was in parallel with the last windings of the stator, the remainder receiving the whole of the return current of the stator. One brush is directly connected to the end of the stator winding and the other to a fixed point in the windings of the auto-transformer, variations of voltage being obtained by different tappings of the transformer.

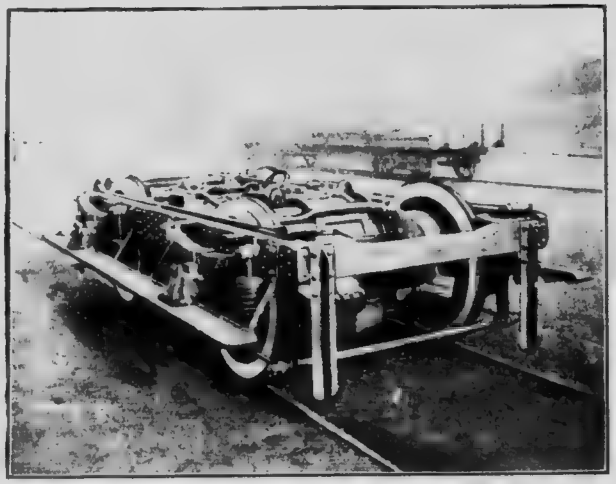

Fig. 844.—Winter-Eichberg Motors Mounted on Truck.

The above will give the reader some idea of the principles involved and the methods employed in controlling monophase commutator motors in traction work. Details of the apparatus will, if space permits, be given in a later section (*see* Chapter XVII).

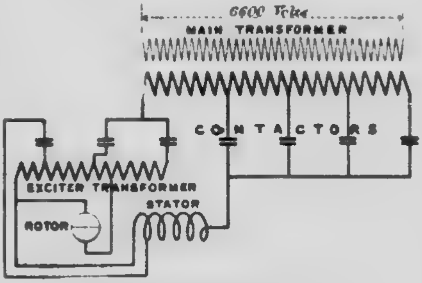

Fig. 845.—Connections of Contactors.

CHAPTER VI

DYNAMO AND MOTOR TESTING

VARIOUS curves showing the relations between the different quantities involved have been given from time to time in the preceding pages, and it will now be convenient to refer briefly to the more general considerations and methods involved in the testing of dynamos and motors, dealing first with continuous-current machines.

There are two points of view from which the testing of any machine may be approached—namely, from the point of view of the manufacturer, and from the point of view of the user. The objects in the two cases are different, but not necessarily antagonistic. The progressive manufacturer will examine the machine not only as to its actual performance, but also in regard to the various details of that performance and the underlying possibilities, which may tend t[illegible] prove the design either in the direction of the production of a r[illegible] [illegible]f still higher efficiency, or of lessening the cost of production by [illegible]ons of details without seriously affecting the efficiency of the mach[illegible] The user, on the other hand, is only concerned with the actual performance of the machine under test, and with the examination of such details as may affect the cost of maintenance or upkeep, and especially with regard to the question of the probable charges for renewals and repairs.

Although, however, the objects of the tests are different, it does not follow that the tests themselves differ greatly. They must, in fact, overlap to a greater or less extent, and of the two the manufacturer's tests—especially in the case of a new pattern of a machine—should be by far the more searching and thorough, and should include all the user's tests. For, after all, it does not pay a manufacturer, in the long run, to turn out a machine which will be costly for maintenance, upkeep, or repairs, as such a policy cannot lead to "repeat" orders or build up a good reputation for any firm.

I.—PRELIMINARY EXAMINATION AND TESTS: MACHINES STANDING

Mechanical Examination.—The apparatus we are dealing with being essentially mechanical, the first tests to apply should be from a purely mechanical point of view, and should consist of a thorough mechanical examination of the various parts of the machine. Then the smooth running of the shaft in its bearings and the methods adopted for lubrication should be carefully examined. Where the machine is required to run for a long period without attention the lubrication should be automatic, and the probable efficiency of the means adopted to secure this (*see* page 175, Vol. II.) should be carefully considered. Intimately connected with the smooth running of the shaft is the balance of the rotating part (*see* page 171, Vol. II.). To test this severely the rotating part should be run at a high rate of speed, and any tendency to chatter in the bearings should be noted. Such chattering is due to want of proper balance, and the tendency to chatter will increase roughly as the square of the speed. If, therefore, the shaft be run at double the normal speed, this evil effect will increase about fourfold.

Next, the methods provided by the design for getting at the moving or fixed parts in the event of a breakdown should be carefully noted. A machine which can be dismantled rapidly, and without the use of special gear or tackle, is *cæteris paribus* a better machine from the user's point of view than one which cannot be so dismantled. The ease with which field-magnet or armature coils or sections can be removed and replaced in the event of a short-circuit is especially important. In the early days armatures were so designed that the removal of a single turn of the winding practically involved the unwinding of the whole or the greater part of the armature. Manufacturers are now much more alive to the necessity for careful design in this respect, and with armatures wound with "former" coils (*see* page 81, etc.) it is possible to keep some spare coils in stock for use in the event of a "burn-out." As motors and dynamos are now used extensively in somewhat inaccessible places, far removed from manufacturing centres—as, for instance, in mining camps in mountainous districts—it is important that a breakdown of this kind should be repairable rapidly on the spot with comparatively unskilled labour. Some manufacturers issue, for such emergencies, elaborate instructions which any good mechanic should be able to follow without special electrical knowledge.

In commutator machines, whether continuous or alternate current, the brushes, brush gear, and rockers require careful examination from a strictly mechanical point of view. Similarly attention should be given to slip rings, brushes, etc., when used on alternate-current machines. The arrangements for holding the brushes against the commutator or the slip rings and the regulation of the pressure with which they are so held, as well as the arrangements for completely removing a single brush for adjustment or replacement whilst the machine is running, should all be carefully tested. The rockers, if any, should move freely, and when clamped should be firmly held, with no danger of being loosened by the vibration of the machine when running.

Electrical Examination.—This will include, first of all, the testing of the *conductivity* of the various conducting circuits by one or other of the methods fully described elsewhere in this book. For shunt windings the resistance can be measured in the ordinary way with a Wheatstone's bridge. The resistance of the armature or of the series magnet coils is better ascertained by the fall of potential method in which are measured the volts required to drive a certain (measured) current through the circuit under test. For bipolar machines the armature resistance is often taken by placing the testing leads on two diametrically opposite bars of the commutator. This method, however, neglects the resistance of the brushes, and the contact resistance between the brushes and the commutator. The test should, therefore, be made either for bipolar or multipolar machines, between the +ve and −ve brush-holders, with the brushes all down. Even then the contact resistance is not the same as when the machine is running, and the most satisfactory test of the actual working resistance of the armature can best be made between +ve and −ve brush-holders, or rings with the brushes all down and the field-magnets as much as possible removed and, in any case, unexcited.

The conductor resistance should always be tested with the machine *hot* as well as with it *cold*. The former is the true working resistance under load, and should be taken immediately after a long run at full load. As the variation of the resistance of copper with temperature is somewhat large (*see* page 756, Vol. I.), the difference between the hot and the cold resistance is by no means a negligible quantity.

The next important electrical test is the *insulation* resistance, which should be measured between each separate circuit and the frame of the machine, and between circuits which in any place lie close together, as for instance, between shunt and series coils, if these are wound on the same bobbin. The methods of measuring such high resistances are discussed elsewhere (*see* page 759, Vol. I., and *infra*). In this case the test should be made with a voltage three or four times that at which the machine has to be worked, and then it becomes a test of the *dielectric strength* of the insulation as well as of its resistance. Testing with a pressure ten or twenty times the working pressure is sometimes advocated; but this is distinctly wrong, for in applying such a test the insulation may be weakened by being overstrained, without actual giving way, and the incipient weakness thus started may increase with time and seriously shorten the life of the insulation.

All the foregoing tests are of interest to both manufacturers and users. Leaving for a time on one side tests of magnetic leakage, etc.—which are only of interest to the manufacturer—and the obtaining of the *external characteristic*, which has been already explained (*see* page 511, Vol. I.) for continuous-current machines, we shall pass, after describing how speeds may be measured, to the most important tests of all—namely, those which determine the *efficiency* of the machine. For this purpose, as being the simpler, we shall deal first with motors and afterwards with generators.

II.—MEASUREMENT OF SPEED

The examination of a machine when standing cannot supply the data necessary to estimate the performance of the machine under working conditions, though it gives valuable information, some of which may be indispensable if the tests are to be regarded as exhaustive. To obtain the most important data the machine should be run at the speed or speeds for which it was designed, and further tests applied. When so running an essential factor is the speed, and methods of measuring speed and variations of speed thus become of paramount importance. A digression on such methods will therefore be appropriate at this point. In practice speed must be observed either directly by means of a *speed counter* or a *speed indicator* or *tachometer*, as it is sometimes called, or indirectly by some carefully devised and convenient method. A widely-used simple form of speed or revolutions counter is shown in Fig. 846. It consists of a movable spindle S S, the ends of which are filed to a pyramidal point, as shown. The spindle has at its middle an endless screw W, which engages in the teeth of the disc E. As there are 100 teeth in the disc, the spindle will make 100 revolutions for each revolution of E. A scale on the disc marks the number of teeth passing any given point Z, and at A there is a projecting metal pin which strikes the second disc H once in every revolution of E, and moves it one tooth further on. As there are ten projecting teeth on H, it will make one revolution to every ten of E, or every 1,000 revolutions of the spindle. A small coned hole being bored axially in the end of the shaft of the motor, the spindle S is held against the centre of the shaft (both axes being in line) by means of the handle G for a measured interval of time—say thirty seconds—and the difference in the readings of the counting wheels at the beginning and end of the time noted. From this difference and the observed time the R.P.M. can be calculated.

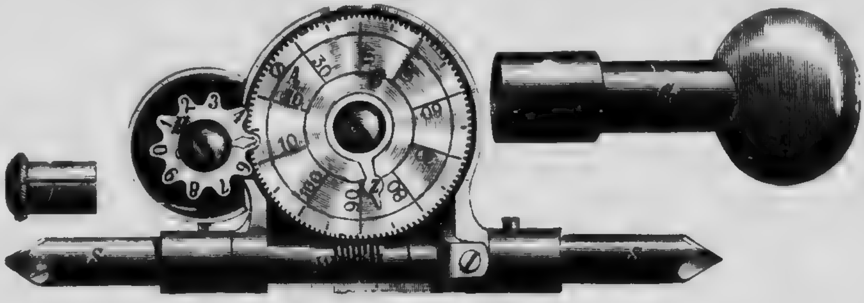

Fig. 846.—[illegible] Speed Counter.

Great care should be taken in applying the speed counting or indicating instrument so that no additional end friction is thrown on the shaft. The method just described does not secure this condition, especially with small motors, as considerable force is sometimes used to press the end of the spindle into the coned hole in the shaft. *Tachometers* or *speed indicators* which can be coupled up with a spiral spring or other flexible connections are therefore preferable. There are several patterns of these, some of which are based on the principle of the centrifugal governor used on steam engines.

Very convenient for electrical work, however, are some of the indirect methods, especially those which use the principle of the Faraday disc dynamo (Figs. 450 and 451, Vol. I.) in combination with a voltmeter, which can be graduated in R.P.M. for the particular speed indicator used. The speed in this case is read off as the deflection on a scale of the pointer of the voltmeter. One of these magneto-electric speed indicators, developed by Dr. Drysdale and the staff in the laboratories and workshops of the Northampton Polytechnic Institute, was described in the second volume of this work, and a similar instrument, differing in details, was subsequently brought out by the Westinghouse Electric Company.

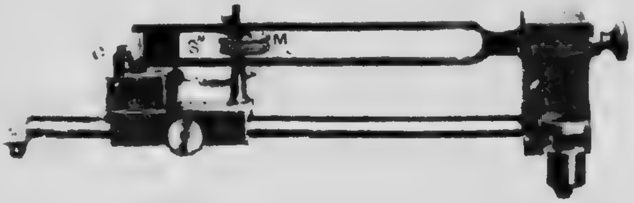

Fig. 847.—Electrically Driven Tuning Fork with Slotted Shutters

The defect already mentioned of most mechanical methods of measuring speed is that their use adds to the frictional load on the machine. This addition, however slight it may be, and though often negligible, interferes with the accuracy of the test, and in the case of small motors may be appreciable. Fortunately, optical methods, depending on the delicacy of the human eye, are available which are entirely free from this defect. They are known as stroboscopic methods, being based on the principle of the scientific toy called the "stroboscope," or "wheel of life," and utilise the property of the eye known as the "persistence of vision," and sometimes regarded as a defect. The physiological fact is that if light falls on the retina for a brief interval, say one-millionth of a second, the impression persists for about one-eighth of a second, which is quite a long period. If during this period other brief images fall on the retina, the two or more images are all seen at once, and if formed on the same part of the retina are superposed.

Bearing this in mind, let a large tuning fork, such as is shown in Fig. 847,* be mounted on a stand so that it can be electrically driven, that is, maintained in vibration continuously for long periods of time. This object is attained by mounting between the prongs of the fork an electro-magnet M, which, when energised, will attract the steel prongs. When the prongs are so attracted the circuit of the electro-magnet is broken at a mercury contact at C, and the prongs spring back only to be again attracted and released. In this way, employing, in fact, the "make and break" principle used in the electric trembler bell, the fork can be kept in vibration for hours if required.

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* This and some of the subsequent figures are taken from articles published by Dr. C. V. Drysdale whilst on the staff of the Northampton Polytechnic Institute.

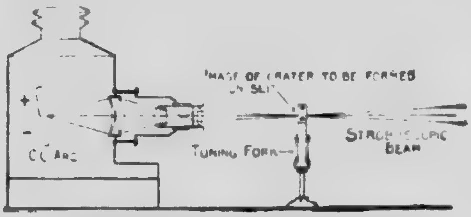

Fig. 848.—Illumination of Stroboscopic Disc.

The fork used is a standard tuning fork, making a convenient number, say 50, of double vibrations per second. On the end of each prong is mounted a shutter S with a central slot parallel to the length of the fork, the two shutters being arranged one behind the other, and the two slots so placed that they are exactly opposite one another when the fork is at rest. If now a beam of light (Fig. 848*) be projected on the shutters and transversely to the fork, it will pass through the slots when the fork is at rest, and also twice during each vibration as the slots pass one another when the fork is vibrating. During the remaining periods of each vibration the light will be eclipsed because each slot will be covered by some part of the other shutter. In this way there is obtained a periodically interrupted beam of light, the flashes following one another at known intervals, which, in the case of a 50-period fork, will be one-hundredth of a second.

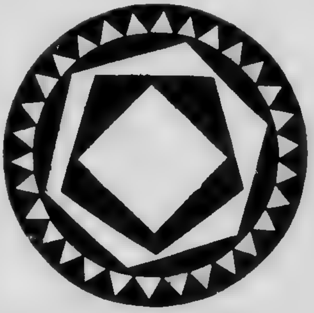

Fig. 849.—Drysdale's Stroboscopic Disc.

The next step is the most interesting, namely to use these periodic flashes to illuminate a pattern on a revolving disc attached, say, to the end of the shaft whose speed it is desired to determine and to observe the effect. Two such patterns, both of which have been found convenient for speed determinations, are shown in Figs. 849 and 850. Fig. 849 is one published by Dr. Drysdale in 1905; it consists of an outer circle of 30 small white triangles on a black ground; inside this a white hexagon, enclosing a black pentagon, which in its turn encloses a white central square. In Fig. 850, published by Prof. Robertson in 1913, there are a series of black triangles on a white ground arranged round successive concentric circles. The innermost circle carries twelve triangles, and the others in order thirteen, fourteen, fifteen, and sixteen triangles respectively. Projecting inwards from the circumference of the card are sixty-four triangles.

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* In this figure, taken from a paper by Prof. Robertson, the fork is represented as being set up vertically.

The effect observed will usually be that some of the figures or rings of triangles will appear to be rotating slowly or quickly in the same direction as the rotation of the shaft, and others in the opposite. One figure or ring may appear to be quite stationary, and if this happens the speed at which the card (and shaft) are revolving can be simply found. For instance, if with the card of Fig. 849 the square appears stationary this will probably be due to the fact that between two successive flashes the square has been rotated by exactly a quarter of a revolution, for if so the new position will exactly cover the old, and the square will appear stationary. If a 50-period fork is being used the intervals between the flashes are 0·01 sec., and in this time the card rotates ¼ revolution; the time for a whole revolution is therefore 0·04 sec., which gives 25 revolutions per second or 1,500 per minute.

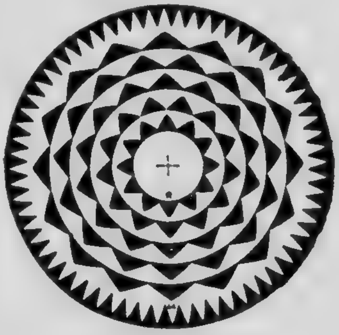
Fig. 850.—Robertson's Stroboscopic Disc.

This is a "probable" explanation of the stationary square; but it is obvious that if between successive flashes the card had been rotated half, three-quarters, or a whole revolution the same optical effect would have been produced, and in these cases the shaft speeds would have been 3,000, 4,500, or 6,000 R.P.M. In a given case it is easy to select the most probable of these possible speeds.

Similarly if the pentagon or hexagon had appeared stationary the effect could be explained by supposing a ⅕th or a ⅙th (or any simple multiple of these fractions) rotation of the shaft between successive flashes, whence the speed could be deduced, a reasonable choice being made between the various speeds, any one of which would explain the effect.

Another possible optical effect is that, for instance, two squares may appear, symmetrically crossed, giving a stationary eight-point star figure. This effect will be produced if the shaft be rotating at 750 R.P.M., being one half the lowest of the above speeds, or any *odd* multiple of this speed; and again it is usually possible, from other considerations, to select the actual speed. Similarly, the appearance of crossed pentagons or hexagons may be utilised.

Finally, if the speed of rotation be not exactly such as to give a stationary appearance, but be near that speed, the particular pattern will appear to be rotating. The rotation will be rapid if the speed be far removed from that which gives the stationary appearance, but will become slower and slower as that speed is approached, until at the exact speed the figure is stationary. If the speed be too fast the rotation of the figure will be in the direction of the rotation of the shaft, but if it be too slow the figure will rotate backwards, an effect which seems "uncanny" when first seen. The explanation is obvious if the reader has followed the explanation of the stationary effects, for the excess or defect in speed displaces the image forwards or backwards, thus giving the impression of a more or less rapid rotation.

The full explanation of the effects seen with the geometrical patterns renders it unnecessary to spend time on a similarly minute analysis of what can be seen with the rings of triangles, plain or Gothic, which appear on Fig. 849 and on the outer edges of Fig. 850. In Prof. Robertson's card, Fig. 850, the successive rings of twelve, thirteen, fourteen, fifteen, and sixteen triangles are very convenient in "running down" tests, to which reference will be made presently. The appearances which may be seen on the inner ring of twelve triangles at the primary (i.e. synchronous) and certain lower speeds are shown in Fig. 851 on an enlarged scale. The quadrant marked "primary speed" would correspond with our 50-period fork to 500 R.P.M. or some simple multiple thereof. At lower speeds, as marked, whilst the speeds are steady, the triangles would overlap as shown, and thus speeds of 250, 166⅔, and 125 R.P.M. and certain multiples of them could be detected.

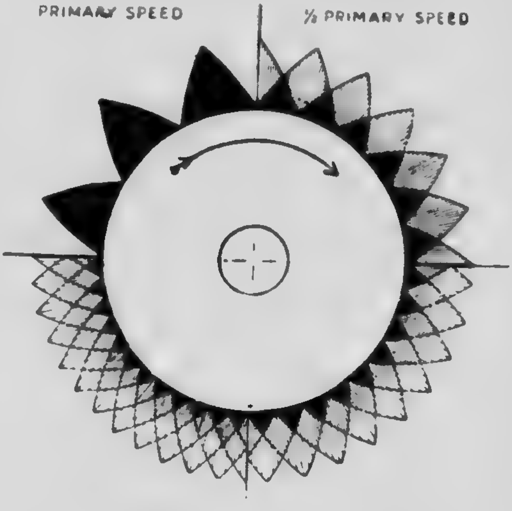

Fig. 851.—Appearance of Card at Primary and Submultiple Speeds.

For speeds which do not give any stationary appearance with the patterns available additional devices are used. One of the most ingenious of these was specially designed by Drysdale to measure accurately the slip of induction motors, and was called by him a "slip-meter." The difference between synchronous speed and motor speed is taken charge of by the varying circumferential velocity of a long, gradually tapering cone, but unfortunately our space does not allow us to describe the apparatus in detail. It is based on the stroboscopic principle.

III.—RUNNING TESTS: ELECTRIC MOTORS

Efficiency.—In testing the efficiency of any machine which continuously transforms energy from one form to another the essential quantities to measure are the energy or power put in, conveniently termed the "input," and the energy or power taken out, also conveniently termed the "output," under normal or varied conditions of working. The ratio of the two—that is, the ratio of the output to the input is the actual or, as it is sometimes called, the *commercial efficiency* of the machine as an energy transformer. Each kind of energy must be measured by appropriate methods, and must, of course, be reduced to the same units before the ratio is taken.

Electrical Measurements.—In the case before us the machine transforms electric power into mechanical power, and simultaneous measurements should be taken of each at different loads and also at different speeds if the motor is required to run at different speeds. The methods of measuring electric power, whether in the form of continuous or single or polyphase alternate currents, are dealt with in other parts of this work (*see* pages 377 and 799 of Vol. I. and elsewhere), and we need only caution the reader that in motor testing the electric power should be measured at the terminals of the machine, and that, if the machine is separately excited, the power used in the exciting circuit must be added to the "input."

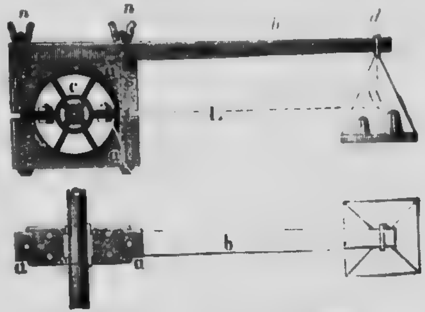

Fig. 852.—Prony's Brake Dynamometer

Mechanical Measurements.—The mechanical power produced (the "output") is most conveniently measured, if not too large, by some form of *absorption dynamometer*—that is, by an instrument which wastefully converts the energy into heat by some form of friction, but which is so designed that in the process the power dealt with can be measured. When the power absorbed is very large, other methods are frequently used.

Absorption Dynamometer.—The simplest forms of absorption dynamometers are rope or other brakes, so arranged that the frictional drag on the brake and the relative velocity of the rubbing surfaces can be measured. Such an absorption dynamometer, known as "Prony's brake," of simple design and widely used for small powers, is represented in Fig. 852. In this brake *c* is a wheel of cast iron, rigidly attached to the axle of the machine to be tested, and held by two wooden clasps or blocks *a a*. The lever *b* is fastened to the upper wooden piece, and supports a scale pan at *d* for weights. The two wooden pieces *a a* are bolted together at *s s*, and their pressure on the wheel can be adjusted by the butterfly nut [illegible] take measurements with Prony's brake, the wheel *c* i[illegible] shaft, the work done by which is to be determined, and the nuts a[illegible] adjusted so that the wooden blocks press the wheel more or less [illegible] The machine is then made to rotate in a counter-clockwise [illegible] with a steady velocity, and if no weights were placed at *d*, the brake would be turned round with the shaft; but weights are placed at *d* so as to keep the beam *b* horizontal, whilst the shaft revolves at the required speed. The friction, which absorbs the mechanical work transmitted to the shaft, produces a torque which is, as explained below, balanced by the torque due to the weights in the scale pan at *d*. As the weight W, the length L of the lever, the radius of the wheel *c*, and the R.P.M. of the shaft are known, the effect in H.P. can easily be calculated.

It has already been explained (*see* Vol. I., page 603) that the power, P, developed by a rotating body is expressible as the product of the *force*, P, *or turning moment*, and the ***angular velocity*** of rotation, or, in symbols, that the power

$$P = 2\pi n T \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

where T is the torque and *n* the R.P.M. If T be measured in pound-feet (or the product of pounds by feet), then P is in foot-pounds per minute, and the H.P. will be

$$\text{H.P.} = \frac{2\pi n T}{33{,}000} \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

whilst the power expressed in watts will be (*see* also Vol. I., page 370)

$$P = \frac{746 \times 2\pi n T}{33{,}000} = \frac{2\pi n T}{44{\cdot}25} \text{ watts} \quad . \qquad (3)$$

The "*output*" P being thus obtained, its ratio to the "*input*" will give the efficiency which can be expressed as a percentage by multiplying by 100. The power supplied to the motor, i.e. the "input," is readily obtained for a continuous-current motor by measuring the volts V and the current C at the *terminals*. We thus get

$$\text{efficiency (C.C. motor)} = \frac{P \text{ (in watts)}}{V C} \quad . \quad . \quad . \qquad (4)$$

$$\text{or percentage efficiency} = \frac{P \text{ (in watts)} \times 100}{V C} \quad . \quad . \qquad (5)$$

With alternate-current motors the electrical input W must be measured by one or other of the methods described elsewhere and we shall then have as above

$$\text{efficiency (A.C. motor)} = \frac{P}{W} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

$$\text{or percentage efficiency} = \frac{P \times 100}{W} \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

In the Prony brake (Fig. 852) the torque T exerted by the shaft is [illegible] to the brake blocks by the friction betw[illegible] [illegible] this torque, tending to turn the brake block[illegible] [illegible] direction, is balanced by the torque [illegible] the [illegible] tion by the weights at *d*, account bein[illegible] taken [illegible] the [illegible] ght of [illegible] and of the lever arm *b*. To calculate the t[illegible] multiplied by the horizontal distance L [illegible] th[illegible] *d* [illegible] line of shaft, whilst for the lever arm [illegible] the product of the weight of the ar[illegible] the [illegible] [illegible] centre of gravity from the ax[illegible]

One of the simplest fo[illegible] [illegible] ke [illegible] for small powers is that shown in Fig. 8[illegible] * which [illegible] wheel and a rope lying in the groove [illegible] wheel revolving counter-clockwise, if a [illegible] sufficient to keep the rope stretched, be [illegible] the left-hand pan, and a heavier weight [illegible] right-hand pan, it is possible [illegible] weig[illegible] that the rope remains [illegible] ary, whilst the wheel revolv[illegible] under it. [illegible] [illegible] nal torque [illegible]

[illegible] the wheel [illegible] by [illegible] the difference of the [illegible] additional de[illegible] [illegible] pensate for changes [illegible] and rope, and for th[illegible] found that a knot [illegible] excrescence at P, will suffice. As M [illegible] aws the [illegible] the knot [illegible] coming on to the groove [illegible] the friction [illegible] resistance, and the rope [illegible] practically stationary, with only a slight oscillation.

[illegible] Brake

The balancing torque on the rope brake is

$$[illegible] = ([illegible] \mathrm{M})(\mathrm{R} + r)$$

[illegible] the radius [illegible] the bottom of the groove and *r* the [illegible] the rop[illegible] (R + *r*) is the total radius measured [illegible] is to [illegible] the rope on the wheel. The power is [illegible] before by [illegible] ng the torque by the speed.

[illegible] dynamometer for small powers is the [illegible] is shown in use, testing an electric motor, [illegible] brake will be better understood by reference [illegible] ch in Fig. 855, in which A B is a flat steel bar [illegible] feet long, and carrying three knife-edges [illegible] the [illegible] nd knife-edges A and B unequal weights a[illegible] [illegible] the central knife-edge C is supported from

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* [illegible] and 858 are [illegible] Prof. Perry's "Applied Mechan[illegible]."

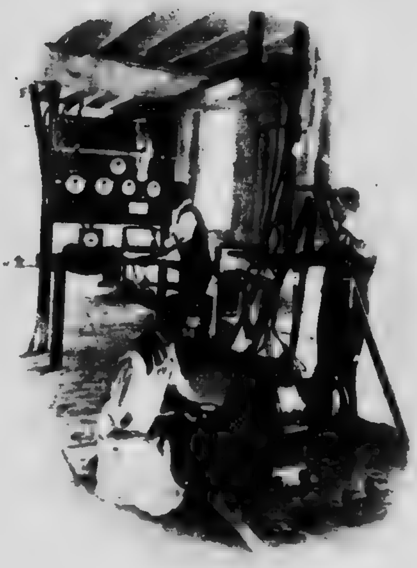

Fig. 854.—Soames' Absorption Dynamometer

the tripod (seen in Fig. 854) by means of a screwed rod, by a hand-wheel on which the support of **C** can be raised and lowered. A number of holes pierce the beam at pairs of points equidistant from **C** on either side, and from a convenient pair of these cords *x* and *y* support a piece of webbing, which passes underneath the pulley **P** of the motor to be tested. The total tension of the cords *x* and *y* can be adjusted by raising and lowering **C** by means of the hand-wheel, and the difference in the tensions by altering the weights **W** and *w*. A pointer *p* projecting upwards from the beam indicates when the latter is horizontal. With a particular pair of weights **W** and *w*, and the motor running at a steady speed the position of **C** is to be adjusted until the beam remains horizontal long enough for speed and electrical readings to be taken. The two observers in charge of these readings appear in Fig. 854, whilst the third observer with his hand on the adjusting wheel keeps the beam horizontal. The method of calculating the mechanical power from the observations will be understood from the foregoing explanations.

For larger powers the brake shown diagrammatically in Fig. 856 may be used. This brake is formed of blocks of wood, fastened to the inside of a flexible hoop-iron strap, the two ends of which are attached at the points **D** and **E** to the lever **DH**, which moves between two stops

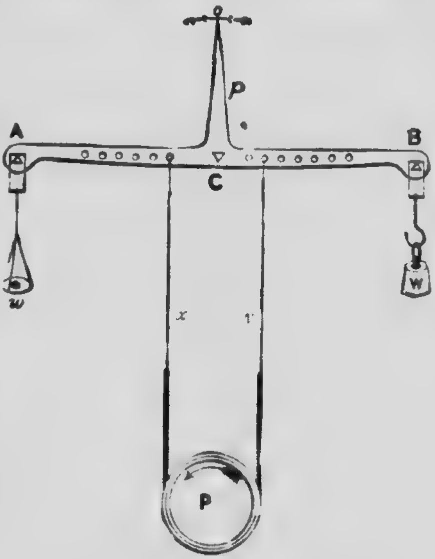

Fig. 855.—Principle of Soames' Dynamometer.

on the upright post. A small weight *w*, or a spring balance, is attached to the end H, and it is obvious that a small difference in the angular position of the lever will produce a great increase in the tightness of the strap. A heavy weight W is hung at C, and when balance is attained with the lever D H clear of the stops, the torque is ($W R - w r$), where R and r are the lever arms as indicated in Fig. 856, from which the power can be obtained as before.

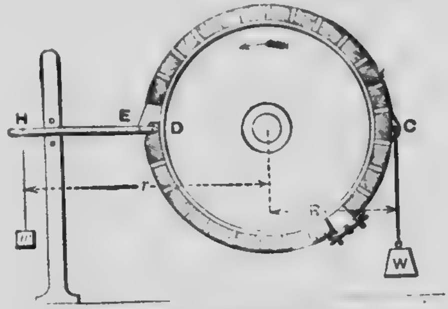

Fig. 856.—Absorption Dynamometer for Larger Powers.

In all these brake experiments the brakes should be kept lubricated with soapy water, for clean water gives rise to spasmodic changes in the friction. The water also serves to carry off some of the heat generated.

IV.—RUNNING TESTS: DYNAMOS

Efficiency.—The direct testing of the efficiency of dynamos is a more difficult matter than the corresponding testing of motors. The object of the tests is to ascertain the ratio of the electrical "output" to the mechanical "input." The former can be measured for all kinds of generators, and especially for continuous-current machines, with ease and certainty. The methods of doing so are described elsewhere in this book.

Dynamometers.—The direct measurement of the mechanical input, however, is not an easy matter, even with small machines of 20 to 30 kilowatts; whilst with very large machines it has not yet been successfully accomplished. It involves the use of a *transmission dynamometer* that is, of an instrument which will transmit the power from the prime mover to the generator and measure it during transmission. Thus, if power is being transmitted from the pulley A (Fig. 857) to the pulley B by means of a belt travelling in the direction shown by the arrows, both free parts X and Y of the belt are in tension, but the tension T_1 in X is greater than the tension T_2 in Y. If v be the linear velocity with which the belt is travelling.

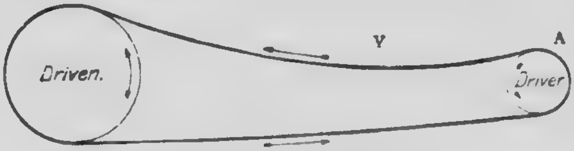

Fig. 857.—Belt Transmission of Power.

The power transmitted = ($T_1 - T_2$) × v, proper units being chosen.

On the assumption that there is no slip in the belt it is easy to ascertain the value of v from the diameter and speed of rotation of either pulley. The difficulty arises when we attempt to measure the quantity $(T_1 - T_2)$ in a belt travelling at a speed of 2,000 to 3,000 feet per minute.

A belt dynamometer designed by Hefner von Alteneck has been much used. It is constructed by mounting two or more idle pulleys in a frame, the two pulleys being closer together than the natural position of the two sides of the belt in travelling from the driving to the driven wheel and back. The belt passing over the inner peripheries of the pulleys is displaced, and tends to draw the frame in the direction of the side on which the tension is the greater. This tendency is counteracted by a spring balance or other mechanical measuring arrangement, and from the force required to balance, together with the geometrical plan of the apparatus, the value of $T_1 - T_2$ can be deduced. Great difficulty, however, is experienced in working the apparatus, owing to frequent and violent oscillations.

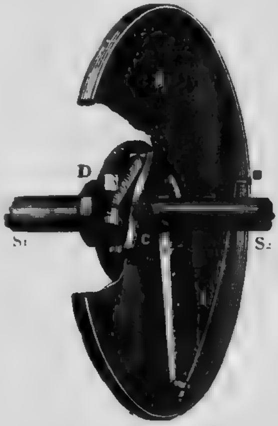

Fig. 858.—Ayrton and Perry's Transmission Dynamometer.

Other transmission dynamometers depend upon the fact that a shaft in transmitting power experiences a turning moment or torque. If, then, the shaft be cut and the two parts mechanically joined by some apparatus which will measure the torque transmitted across the gap, the power transmitted can be readily calculated. The difficulty is to design a satisfactory measuring arrangement which shall allow the torque to be observed as the shaft rotates. Such a form of *dynamometer coupling*, designed by Professors Ayrton and Perry, is shown in Fig. 858. Instead of the two coupling discs D and C, keyed respectively to the shafts S_1 and S_2, being connected as usual by bolts, they are connected by spiral springs S. When power is being transmitted from D to C these springs are stretched, and the disc C is displaced in an angular direction with respect to D. Now C carries the first of a set of light levers or links E, which are attached to the disc A by a pin near its periphery. The disc A is rigidly attached to D. If the driving shaft is turning counter-clockwise, it will be found that the point B at the end of the levers will be moved inwards. To observe the amount of motion B carries a bright bead, and if a scale be held level with the shaft and horizontally in front of A, the points at which B passes behind the scale can be read off and the deflection of B determined. The surface of A is dead-blacked to facilitate the reading. The value of the deflections can be ascertained by a static calibrating experiment, but one of the difficulties in practice is the action of the centrifugal forces on the springs and on the light levers. This coupling has been used for belt transmission by means of pulleys on an intermediate countershaft.

The fact that when a shaft is transmitting power the shaft itself is twisted has been utilised to measure the amount of power which is being transmitted.

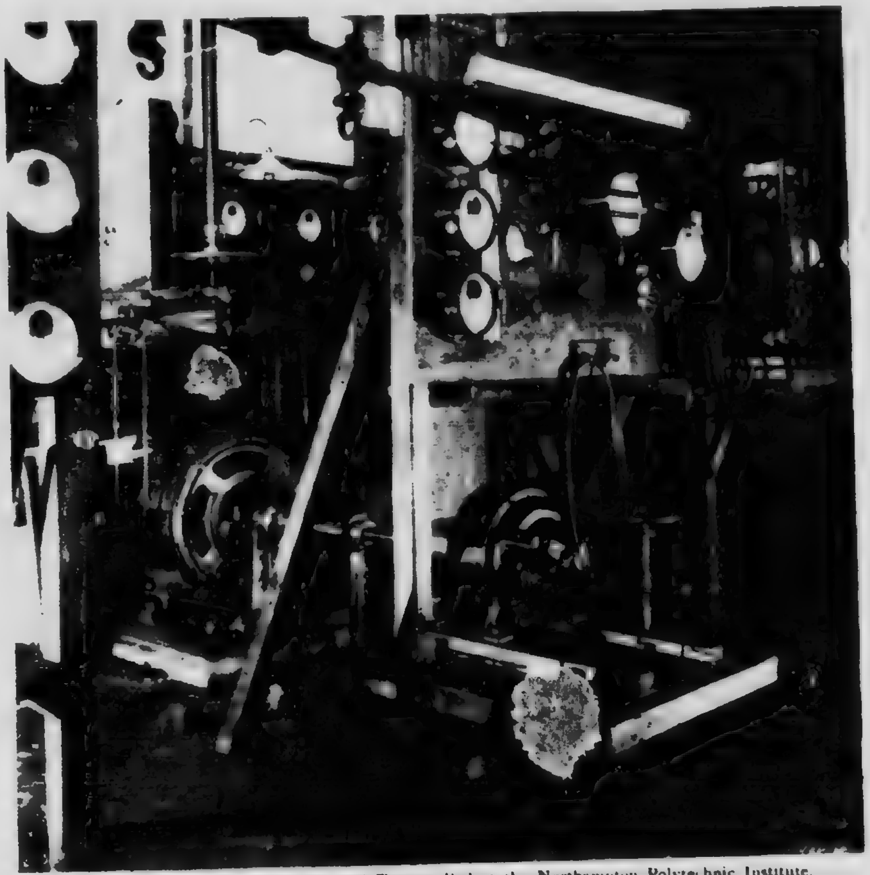

Fig. 859.— Cradle Dynamometers and Testing Bed at the Northampton Polytechnic Institute.

The law connecting the angle of twist or torsion with the torque to which the shaft is subjected is similar to that which obtains in the controlling suspensions used in many delicate electrical measuring instruments described elsewhere in this book. In other words, the torque is proportional to the angle through which the shaft—or, more conveniently, a given length, say unit length, of the shaft—is twisted. The difficulty, of course, is to observe this angle when the shaft is running at a high, or even at any, speed, and much ingenuity has been devoted to the solution of this difficulty. Hitherto the method has been chiefly successful in the measurement of the power transmitted from the engines of a steamship to the propeller, but it is quite capable of development, and has been developed, in other directions.

Cradle Dynamometers.—For many years it has been recognised that the force which exists between the armature and the field magnets of a dynamo or motor due to the electro-magnetic actions might be utilised for the purpose of measuring the torque acting on the rotating shaft and rotor In fact, in the clearance space between the two there exists a subtle frictional action as potent, as we have seen elsewhere, for absorbing power as the friction surfaces of a Prony brake, but, unlike the latter, not necessarily destructive for useful purposes of the power handled. The problem of measuring this torque is not a difficult one, but, as we shall see presently, the details have to be carefully thought out.

Without going into the history of the development of this form of dynamometer, it will suffice to describe here one particular example, and for this purpose we select the testing set designed by Dr. C. V. Drysdale for the laboratories of the Northampton Polytechnic Institute, London. A view of the apparatus as set up in the laboratory is given in Fig. 859,* and some of the details in the subsequent figures. The main parts of the apparatus are the dynamometer machine, seen in the background, with its switchboard and electrical controlling gear; the adjustable testing table, seen in the foreground, on which the machine to be tested is mounted; and the switchboard, on which are assembled the various instruments and switches for measuring and controlling the electric power of this machine.

A diagrammatic side view of the mechanical arrangements is given in Fig. 860, and an end view, with the machine M removed, in Fig. 861. The dynamometer machine G, which is a four-pole eight-kilowatt Westinghouse continuous-current machine, has its stator or field magnet supported from the overhead screw P by the beams and linkages shown. All the movable joints of the points of support consist of knife edges designed to reduce the friction to a minimum. In line with the horizontal diameter of the machine are the projecting arms K K (Fig. 861), at the ends of which are rods A A, also supported on knife edges, on which balancing weights can be loaded. Whether, therefore, the machine be running or standing, its stator can be balanced so that it hangs quite clear of the stops *p p*. When the machine is standing it is in balance with equal weights on the two rods A A; but when it is running with its field magnets excited and currents in the armature conductors, the rotating armature will tend to drag the stator round and the torque between them must be balanced by adding weights to the proper rod A. The machine is designed to run at any speed

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* This and the following figures are taken from an article by Dr. Drysdale in *Engineering*, Vol. LXXX., page 679 (1905).

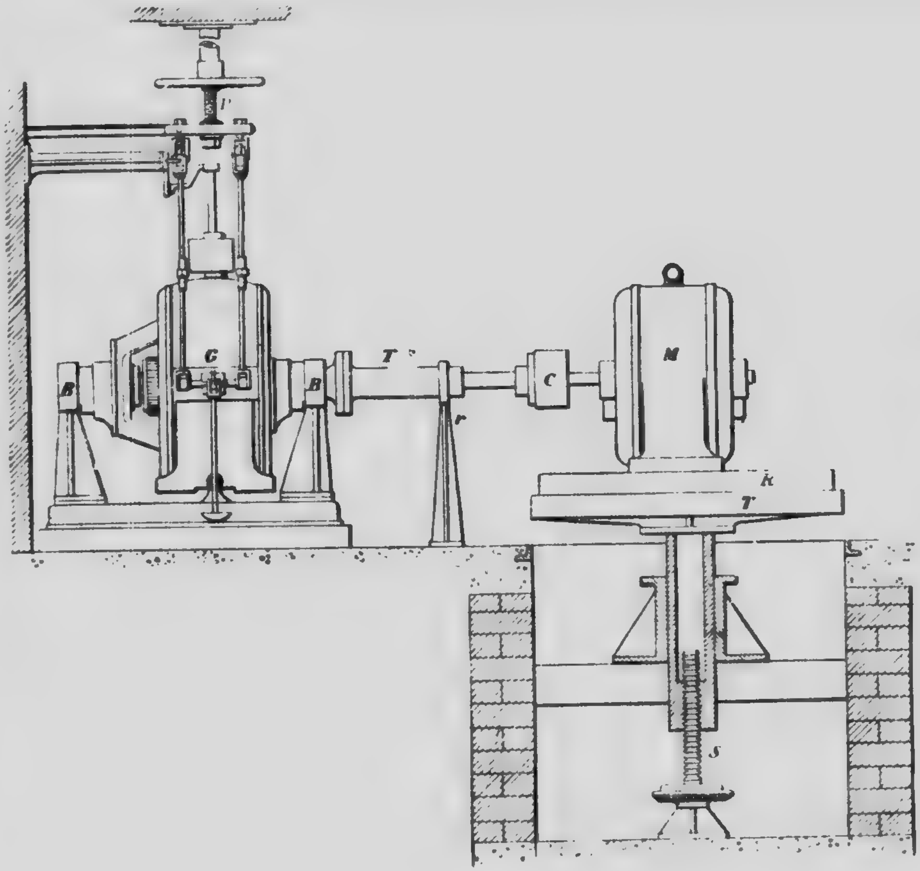

Fig. 860.—Cradle Dynamometer and Testing Bed (Side View).

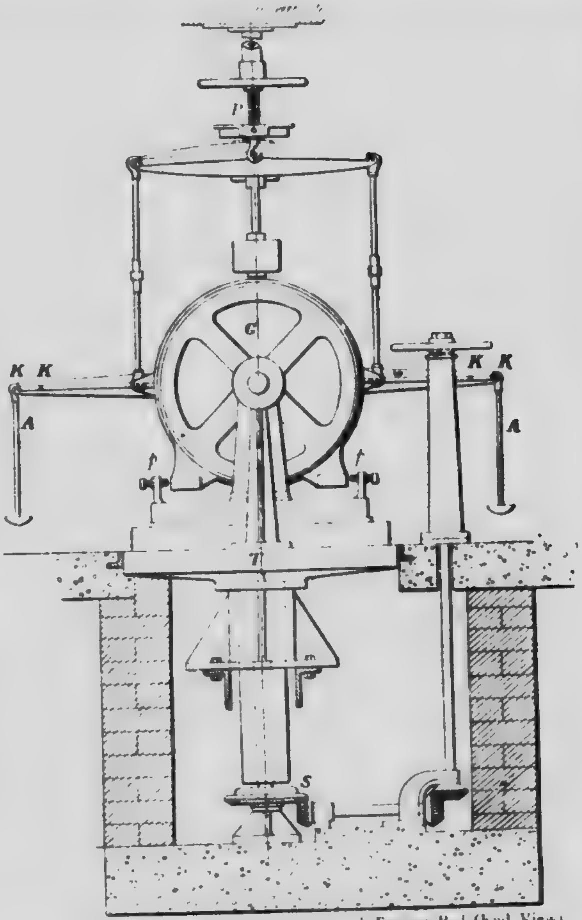

Fig. 861. Cradle Dynamometer and Testing Bed (End View).

from 750 to 160 R.P.M., and when driven at any of these speeds as a generator will give 100 volts, which is the voltage of the Institute's supply circuits. The shaft of G is supported by ball bearings B B on a rigid base, and is coupled to a telescope shaft T S supported by a third bearing *r*. The inner rod of this shaft can be moved backwards or forwards about a foot in the direction of M, and carries on its end a self-centering jaw chuck C which can grip the end of the axle of the machine M which is to be tested. This machine, as already explained, is mounted on a table T carrying rails R, the vertical level of which can be adjusted by the screw S and the bevel gearing shown in Fig. 861.

The machine M may be either a motor or a dynamo. If it be a motor it receives the electric energy, continuous or alternate current, for which it is designed, from the circuits coming to the front switchboard in Fig. 859, and drives the machine G as a generator. The input of M is measured at its terminals, and its output is measured by its speed, and by the torque it delivers to the shaft T S, which is measured by the weights on A A, and the constants of the apparatus. In this way any type of motor for which the requisite electric energy is available can be rapidly put in position, coupled up, and tested.

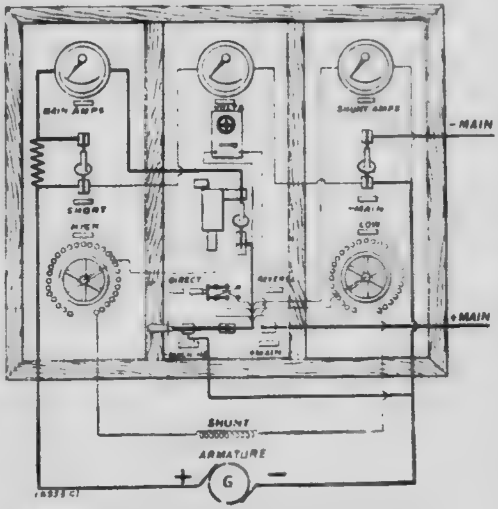

Fig. 862. - Electrical Connections for the Cradle Dynamometer.

The most interesting point about the apparatus is that the energy delivered to G is not wasted: G, acting as a generator, delivers its electric power to the supply mains of the building, and the power so delivered is used for any purpose, either lighting or otherwise, for which there is a demand at the moment. In fact, G is paralleled with the other sources of supply. The electrical connections for this and the reverse method of working are shown in Fig. 862. The dynamometer machine is shunt wound, and in the exciting circuit there are two rheostats, one for a coarse and the other for a fine adjustment over a wide range; there is also a reversing switch in the exciting circuit, so that the machine can be run in either direction. The building mains are brought in through single-pole switches, by which they can be disconnected entirely, so that G may be run up either on its own resistance or an artificial load. The other connections are self-explanatory.

The machine G can also be driven as a motor from the supply mains, and can then drive the machine M as a generator, the power passing between the two machines being measured as before. In this case, however, the output of M will, as a rule, have to be absorbed by a resistance load and wasted. Its amount will be measured with the proper instruments on the front switchboard of Fig. 859.

It should be noted that the dynamometer described is essentially a transmission dynamometer, though the power passing either way may be wasted instead of being utilised.

Testing of Continuous-current Dynamos.—The completion of the "efficiency" test, which is the test of greatest interest to the user, is a simple matter in the case of continuous-current dynamos if the difficulties of measuring the mechanical "input" by some form of transmission dynamometer have been successfully overcome. The speed being kept constant, all that is necessary to complete the test is to measure the electrical "output," which can be readily ascertained by measuring the current in "amperes" on an ammeter placed in the external circuit so as to measure the full current on that circuit and the pressure in "volts" on a voltmeter placed across the terminals of the machine. The product of these two quantities will give the power in "watts." We then have at once that the efficiency

$$\eta_{\text{(per cent.)}} = \frac{\text{output}}{\text{input}} \times 100 \quad . \quad . \quad . \quad . \quad (0)$$

Care must be taken that the units in which the numerator and denominator are expressed are the same, and therefore before applying the equation the input, which has probably been measured in mechanical units, should also be expressed in "watts." The relations of the various units have been fully explained elsewhere. (*See* pages 337 to 381 and 801, Vol. I.)

In addition to the efficiency, the performance of the machine under varying conditions of load is also of interest to the user. This performance is usually exhibited graphically in the shape of "characteristic curves," which have been fully dealt with in Vol. I. (*see* pages 510 to 513). The method of obtaining such curves is obvious, as they simply require ammeter and voltmeter measurements for the different loads. It must not be overlooked that for any curve the speed is supposed to be constant throughout. Should the speed vary, a speed correction must be applied to the readings actually obtained; the method of correction depends on the type of machine, but the principles underlying it have been already fully explained.

The cool running of the machine under load is also of interest to the user, for, as explained elsewhere, the heating practically limits the output It is therefore usual to run the machine under full load or overload for a specified time (say four or six hours), and to ascertain the excess temperature of various salient parts at the end of the run. This test is referred to again later on. (*See* pages 853 to 858, *infra.*)

Testing of Alternators.—The application of the user's tests to alternators of moderate size involves much the same difficulties as are met with in testing continuous-current generators. The chief tests are those which give the consumer particulars of the efficiency and heating of the machine under different practical conditions of load. The first of these involves the measurement of the mechanical "input" and the electrical "output." In regard to the latter there is no difficulty, as it requires only well-known methods of measuring alternate-current power. (*See* pages 799 to 807, Vol. I.) The difficulties of measuring the "input" have been already considered. With most alternators, however, the fact of separate excitation must not be overlooked, the power so expended being of course part of the "input," though it does not reach the machine as mechanical power. The heating tests (*see also* later, pages 853 to 858) should be full-load tests, and here again a new consideration is introduced in the power factor of the load, because the large idle currents necessary for low power factors necessarily affect the heating of the generator.

The external characteristics of an alternator, which are also obviously of interest to the user as they show the electrical behaviour of the machine under different loads, are not so readily obtained as for a C.C. machine; moreover, the external excitation to be supplied—a matter which does not trouble the user in self-exciting machines—has become important, and has to be taken into account. With alternators this predetermination of the performance of the machine is usually indirect, and is based upon "short-circuit" and "no-load" tests, the taking and interpretation of which have already been described. (*See* pages 337 to 342, *ante.*)

Testing of Large Generators.—For large machines, whether continuous-current dynamos or alternators, direct tests cease to be practicable, both because of the difficulty of measuring large amounts of mechanical power by transmission dynamometers, and also because of the inconvenience and expense of supplying such large amounts of power for mere testing purposes and the difficulty of absorbing the electrical "output" on satisfactory loads. When the machines are large, therefore, indirect methods of testing are applied, and prominent amongst them are the Hopkinson method and its modifications, which will be dealt with in a separate section.

V.—LOSSES IN DYNAMOS AND MOTORS

It will be convenient at this stage to refer briefly to the various sources of loss, the existence of which renders dynamos and motors imperfect as transformers of energy. The unavoidable losses may be summarised as follows :—

(i.) The $C^2 R$ losses in the copper conducting circuits. These have been fully referred to at pages 514 to 516, Vol. I., and can be readily calculated when the various currents and resistances are known, but the value of the resistance when the circuits are "hot" should be the value used.

(ii.) The losses due to eddy currents.

(iii.) The losses due to hysteresis in the masses of iron in which the magnetisation is being rapidly reversed.

(iv.) The losses due to mechanical friction at the brushes and the bearings, to which should be added "windage" losses which more recent work has shown to be appreciable.

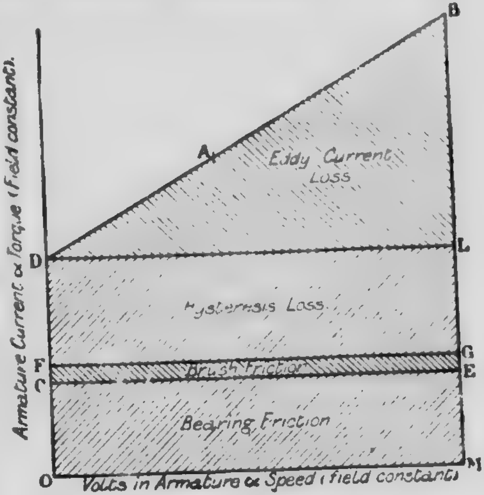

Fig. 863.—Separation of Dynamo Losses.

The following is a simple method, published simultaneously by Kapp and by Housman in 1891, for separating the losses in a continuous-current armature due to (ii.) from those due to (iii.) and (iv.). The method depends upon the fact that the eddy current **losses** are proportional to the **square** of the speed, whilst the hysteresis and mechanical friction losses are assumed to be proportional to the speed simply.* Let the fields be separately excited, and the armature run quite light as a motor at various speeds. The currents supplied at the corresponding speeds of rotation are to be measured and also the back E.M.F.S, which can be obtained by observing the terminal P.D. and deducting the lost volts. Since the field is constant this back E.M.F. (E) is proportional to the speed, and may be denoted by $k\,n$, where k is a constant and n the speed. The results are to be plotted in a curve (Fig. 863), with values of speed horizontal and armature currents (C) vertical. The result will be a straight line A B, which, if produced backward, will cut the vertical axis in D. Now if W be the watts wasted in overcoming the sources of loss (ii.) (iii.) and (iv.), we have

$$W = n\,H + n^2\,F \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where H and F are coefficients to be determined.

---

* Later researches have shown that this assumption is not strictly true, and that the real conditions are more complicated both as regards bearing friction and "windage" or air friction.

But $W = EC = knC$

and therefore $knC = nH + n^2F$

whence $kC = H + nF$

and $$C = \frac{H}{k} + n\frac{F}{k} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

which shows that the connection between C and n should be a straight line such as is given in Fig. 863. From this diagram we have

$$\frac{H}{k} = OD \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$\frac{F}{k} = \tan BDL \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

whence H and F can be found, for k is already known. It is further obvious that the areas BDL and $LDOM$ (representing "torque" multiplied by "speed") are proportional respectively to the power consumed in the eddy current losses and the hysteresis and mechanical friction losses of equation (1).

If two machines are arranged as in Fig. 864 for the Hopkinson test it is possible to separate the mechanical friction losses from the hysteresis losses as follows:—Let one of the machines as a motor, with its fields separately excited, drive the other; now measure electrically the power required (i.) to run the motor armature at full speed, with the second machine disconnected, (ii.) to run the two armatures coupled together, but with the field-magnets of the second machine unexcited and its brushes up, and (iii.) to run both armatures with the brushes of the second machine rubbing on the commutator, but with its fields still unexcited. The difference between (i.) and (ii.) will give the power lost in bearing friction and windage in the second machine, and the difference between (ii.) and (iii.) the power lost in brush friction. From the data so obtained the space $DLMO$ (Fig. 863) can be further divided into the rectangle $OCEM$ giving the bearing friction, the rectangle $CFGE$ giving the brush friction, and, by difference, the rectangle $FDLG$ showing the loss by hysteresis.

Where two similar machines are not available for a Hopkinson test the above experiment can still be made, provided a motor usually referred to as an auxiliary motor be available of the proper capacity and speed to take the place of the first machine.

VI.—THE HOPKINSON TEST FOR DYNAMOS AND MOTORS

The difficulty of making a satisfactory transmission dynamometer to measure large amounts of power led Dr. John Hopkinson in 1886 to devise an electrical method of testing, the principles of which are shown diagrammatically in Fig. 864. Two exactly similar continuous-current machines M_1 and M_2 are set up with their shafts in line and coupled together at P.

The coupling P is in the form of a pulley, which can be driven from a small steam- or gas-engine, a transmission dynamometer of the Siemens or other pattern being placed on the belt. An additional resistance is inserted in the shunt field-magnet circuit of M_2 so that when the normal speed has been attained the excitation of M_2 is less than the excitation of M_1. The + terminals A_1 A_2 are then connected together, and also the – terminals B_1 and B_2. On account of the lower excitation the P.D. of A_1 B_1 is greater than the P.D. of A_2 B_2, and consequently a current flows round the closed circuit in the direction shown by the arrows. In this circuit the machine M_1 acts as a generator, absorbing mechanical power from the shaft S_1 S_2, and delivering electrical power to the circuit A_1 A_2 B_2 B_1, whilst the machine M_2 acts as a motor, absorbing electrical power from the same circuit and delivering mechanical power to the shaft S_1 S_2. By adjusting the excitation of M_2 the current C, as measured by the ammeter G, can be made the full-load current of either machine, or any fraction of the full load current.

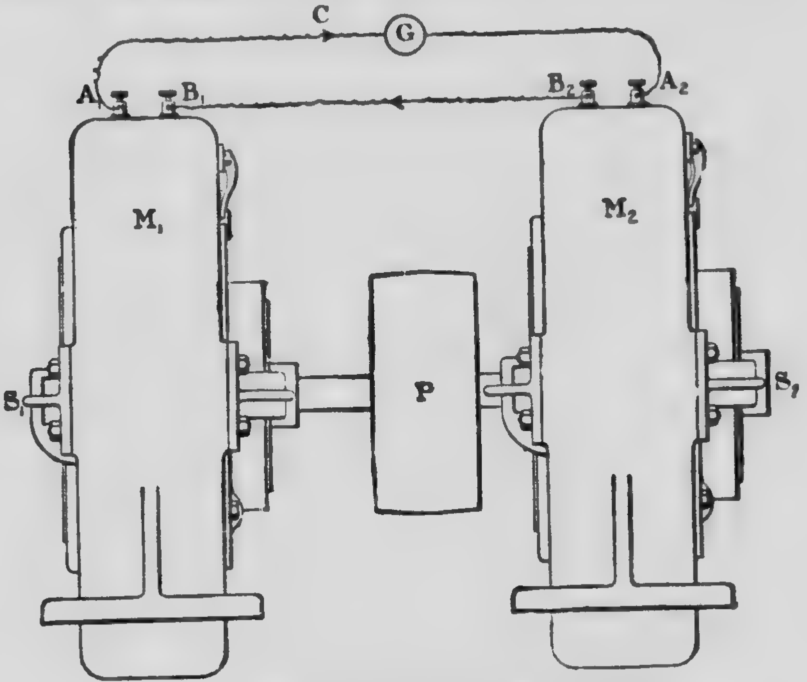

Fig. 864.—Diagram of Machines Coupled for the Hopkinson Test.

Now in the double transformation of the generator and the motor there is necessarily some power lost in frictional heat, mechanical, electrical and magnetic, owing to the machines not being perfect as transformers of energy.

The power so lost is supplied mechanically to the pulley P by the belt from the steam- or gas-engine, and the power thus supplied is measured by the transmission dynamometer through which the belt runs. The output of the generator M_1 is measured electrically, and is the same as the input of the motor M_2, for the loss in the connecting leads is negligible.

If we now assume that the efficiency of the two machines is the same whether working as generators or motors under practically the same load the above measurements will enable us to find this efficiency. Thus-

Let P_1 = the output of the generator M_1 and the input of the motor M_2
,, P_2 = power supplied by the pulley P
,, P_3 = the output of the motor M_2
,, x = the efficiency of either machine at the load P_1
then $P_3 = x\,P_1$
,, $P_1 = x\,(P_2 + P_3)$
whence $P_1 = x\,(P_2 + x\,P_1)$

$$\text{and } \left(\frac{1}{x} - x\right) = \frac{P_2}{P_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Hence, if we know P_2 and P_1, the value of x can be calculated. The equation (1) to be solved is a quadratic equation, and therefore has two solutions. It will, however, be found on examination that one of these is negative and greater than unity, and therefore is inapplicable to this particular problem. The other is positive and less than unity, and is the one to be adopted as the applicable solution.

The great advantage of the Hopkinson method is that, when the efficiency of the machines is fairly high, the amount of power P_2 wasted in the test and which has to be measured mechanically by the transmission dynamometer is very much less than the load P_1 of the machine. Thus if the efficiency of each machine be 95 per cent., P_2 is not one-tenth of P_1, and at 90 per cent. it is less than one-fifth. Below this the ratio of P_2 to P_1 rapidly rises, and at 75 per cent. efficiency the power to be supplied to the pulley is over 43 per cent. of the power on the shaft.

An objection to the method is that although at high efficiencies the assumption that the generator and motor have the same efficiency is sufficiently correct for practical purposes, it ceases to be so at lower efficiencies and the method fails. Another objection is that the method requires the machines to be identical in construction in order that the above assumption may be approximately true. They must, in any case, run at the same speed.

Notwithstanding these objections, the method is so convenient that in one or other of its modified forms it is widely used for testing dynamos of large size. The most important modification—made by Kapp and others—is that the power wasted in the double transformation should supplied electrically to the connecting wires instead of mechanically to the connected shafts. The advantage is that power so supplied can be much more easily measured, as we have already shown, than mechanical power.

Kapp's diagram of connections for this test is given in Fig. 865.* The two machines under test are G and M, which are represented diagrammatically as shunt machines excited by the coils s_g and s_m respectively. The machine G is to act as the generator, and the machine M as the motor; and in order that the latter may generate a less E.M.F. than the former, a resistance R is introduced into its exciting circuit, but in other respects the machines are similar. The motor M is shown as driving the generator G by means of the belt, whilst G supplies current to drive M electrically through the thick line circuit as shown.

The power lost in the double transformation and in friction of various kinds is supplied to the electric circuit from the third machine X, which is connected up as shown to the three-way switch K, which can either be placed in the position "1," as shown in the diagram, or in the position "2," shown by the dotted line. There is an ammeter A in the main circuit between the points, to which the two lower contacts of K are connected. Now, if the switch be in position 1, the ammeter measures the full current C_1 flowing to the motor, partly supplied by G and partly by X through K. If, on the other hand, the switch be in position 2, the current from X no longer passes through the ammeter, which now measures the current C_2 of the generator G.

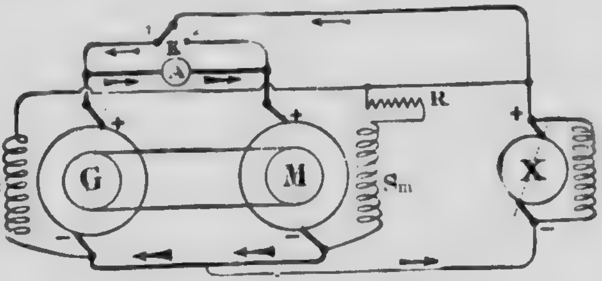

Fig. 865.—Kapp's Modification of the Hopkinson Test

The ratio of the currents C_2 to C_1 is the over-all efficiency of the combination since it is the ratio of the total output to the total input, if we assume that the fall of potential along the wires between the machines is negligible; and if we assume further, as is usual, that the efficiencies of G and M are equal, the same ratio is the *square* of the efficiency of either machine. This proposition may be quite simply proved as follows:—

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* From Dr. S. P. Thompson's "Dynamo Electric Machinery."

Let x = the efficiency of either machine at the particular load used in the test,

,, P = the power transmitted mechanically from M to G

then $x = \dfrac{P}{V C_1}$ . . . . (1)

where V is the P.D. between the brushes of either machine

also $x = \dfrac{V C_2}{P}$ . . . . (2)

Hence, by multiplication—

$$x^2 = \frac{P}{V C_1} \times \frac{V C_2}{P} = \frac{C_2}{C_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3) \quad \textit{Q.E.D.}$$

We have, therefore, the efficiency of either machine—

$$x = \sqrt{\frac{C_2}{C_1}}$$

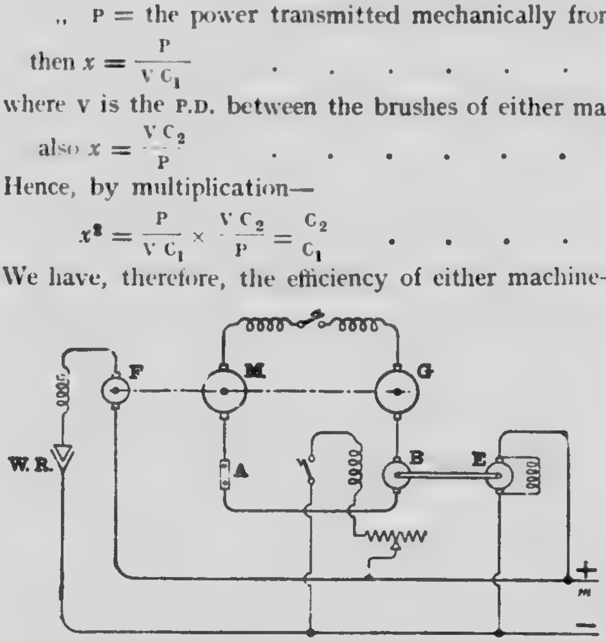

Fig. 866.—Electrical Connections for Hopkinson Test in Factory.

and the test is reduced to taking two readings on an ammeter, than which it is difficult to imagine anything simpler. The general remarks, however, already made on the method must not be overlooked, and the copper losses in the field coils must be taken into account.

If there be an appreciable fall of potential in the leads or connecting wires, voltmeters can be used to measure the P.D. between each pair of brushes, and this can be introduced into the equations, but the unknown and unmeasured power P transmitted mechanically from M to G will cancel out of the final result. It is further obvious that if the efficiency of one machine has been carefully ascertained independently at all loads, the method can be used to determine the efficiency of the other, either as a generator or as a motor, provided the electrical magnitudes are of the right order.

The diagram given on page 843 shows the connections for making the test for shunt-wound machines. The modifications for series-wound machines are fairly obvious, but an interesting case is that of railway motors in which large numbers of machines are turned out which are all built to the same design and specification, and which are therefore peculiarly well adapted for the above test. The connections for carrying out the test in the shops of the General Electric Company at Schenectady are given in Figs. 866 and 867. The electrical circuits are shown in Fig. 866, and the mechanical connections in Fig. 867.* As in the previous diagram, M and G denote the machines under test which are acting as motor and generator respectively, and in Fig. 867 these machines are shown coupled together through their gear wheels on the same shaft, on which also is a small motor F, the function of which is to supply the iron and frictional losses of the two machines. In the principal circuit (Fig. 866) the armatures and field coils of M and G are all in series, and there is included a booster B belt driven by a small motor E, also, as is F, supplied with power from the supply leads *m m*. An ammeter A is inserted in this circuit to measure the load current. The function of B is to make good the drop of voltage caused by resistance, and thus to supply the energy wasted in the resistance of the machine; in other words, to make good the copper loss. It will be noticed that the field of the booster is excited from the supply mains through an adjustable rheostat, and that there is a water rheostat W R which regulates the power supplied to F. With the explanation already given the reader will have no difficulty in deciding what measurements are necessary; he should not overlook the power supplied to the shaft by F.

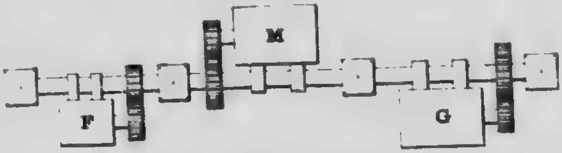

Fig. 867.—Mechanical Connections for Hopkinson Test in Factory.

It has been pointed out above that one great advantage of this method of testing is the facility with which it can be applied to large machines. Machines can be run for hours under full load without the expenditure of an excessive amount of power, a point by no means negligible when large machines are in question. Two large continuous-current machines are shown in Fig. 868 coupled ready for the Hopkinson test in the works of Messrs. Mather and Platt, with which Dr. John Hopkinson was intimately associated when he first published the method. In this case the two machines are not of equal rated output, one—that on the left—being a machine designed to give 880 kilowatts at 230 volts when running at 150 R.P.M., but capable of carrying overloads up to 1,150 kilowatts for two hours and 1,320 kilowatts for a few minutes. The rated output of the right-hand machine is 675 kilowatts at 135 to 150 volts when running at 150 R.P.M.

In the test the machines were joined up as shown in Fig. 865, and were run at 160 R.P.M., which was a little over their rated speed. The smaller machine on the right was run as a motor with a current of 4,520 amperes at 180 volts, being its full-load current but an excess voltage. The other machine was run at the same voltage and at about full-load current as a generator; it was, of course, under-excited on its shunt fields, but the copper losses in both armatures would be full-load losses. The test, which was really a heat test and not an efficiency test, lasted six hours with no greater loss of energy than would be involved in a full-load test of a 120-kilowatt machine, though the combined load of the two machines was about 1,500 kilowatts. To drive the smaller of these machines at full load would have required a 900 or 950-H.P. engine, and would have monopolised this engine with its boilers, etc., for the six hours of the test.

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* From a letter of Mr. F. M. Denton in the *Electrician*, Vol. LXX., page 813 (1913).

Application to Alternators.—The principle of the Hopkinson test can also be utilised for testing large alternators under approximately full-load conditions without calling upon the resources of the test room to supply more power than is necessary to make good the losses caused by the inefficiency of the machines. Two such two-phase alternators, each having an output of 1,350 kilowatts at 100 R.P.M. and 50 ∿, are shown in Fig. 869, mounted on the works test-bed and coupled together on a temporary shaft. The machines were built at Siemens Bros.' Dynamos Works at Stafford, and were practically identical. To carry out the Hopkinson test the frame of one is displaced relatively to the other so as to give a phase displacement of about 25 electrical degrees in the E.M.F.s in the complete circuit of the two machines. In this case the leading machine was run as a generator with an output of 1,350 kw. (Cos ψ = 1), and the

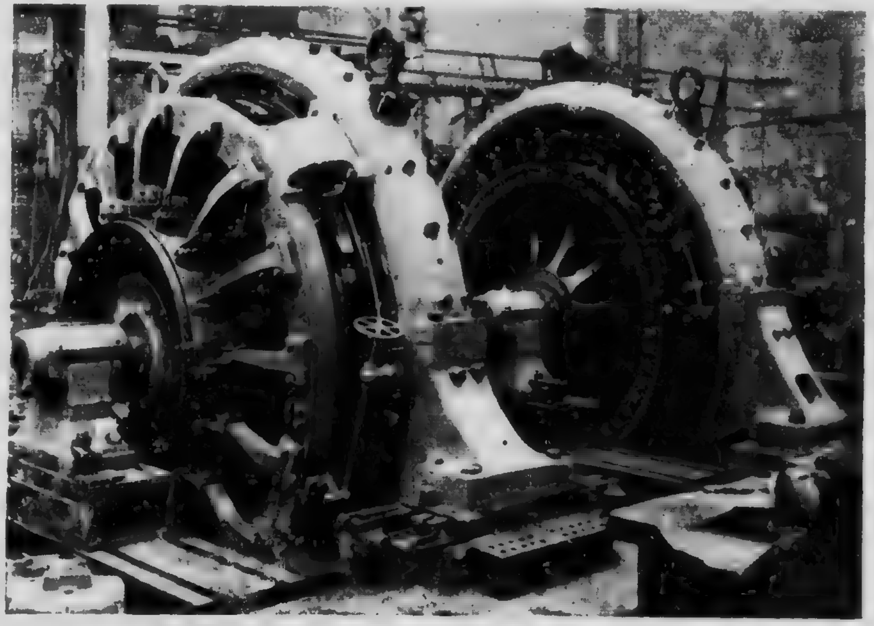

Fig. 868.—Two Large Mather and Platt Dynamos Coupled for Testing.

lagging machine with a slightly reduced field as a motor. The losses, mechanical and electrical, are supplied by the continuous-current motor,

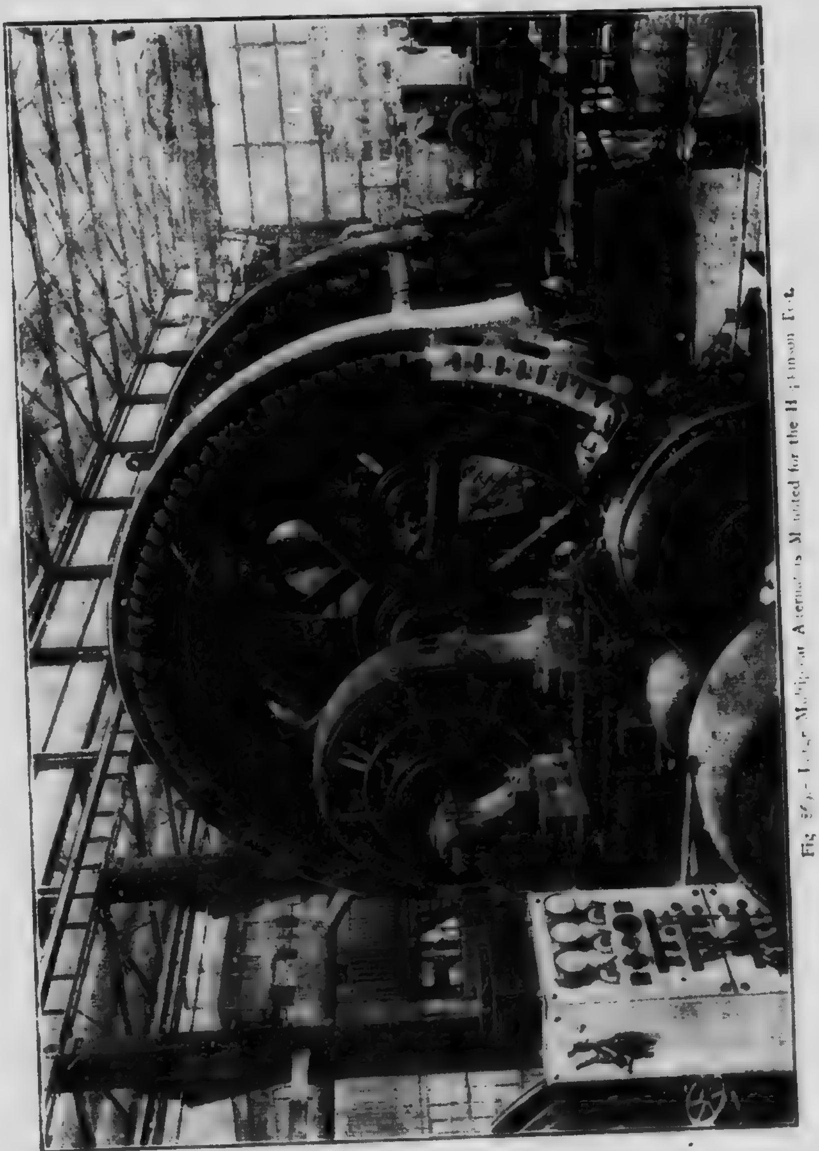

Fig. [illegible].—Large Multipolar Alternators Mounted for the Hopkinson Test.

which can be seen directly coupled to the shaft. With these arrangements, when the necessary adjustments had been made, the full-load circulating current of 205 amperes was very steady with no signs of hunting or surging.

The theory of the method, which, in the main, is the same as for the continuous-current case, is readily explained by the vector diagram given in Fig. 870. Let O G be the generator E.M.F. and O M the motor E.M.F. lagging in phase behind direct opposition to O G. The resultant E.M.F. is O E operating in the closed circuit of the two armatures in series. As this circuit has a low resistance the current is practically in quadrature with O E, and may be represented by O C. The power absorbed by the electrical circuit in the generator is the product* O G × O C, which is +ve, whilst the product O M × O C is —ve, and denotes power given electrically to the motor.

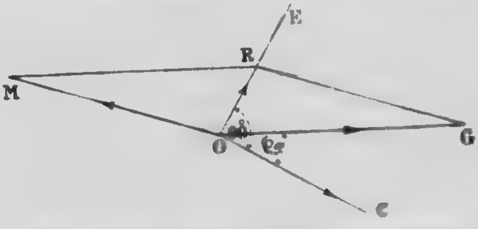

Fig. 870.—Vector Diagram, Hopkinson Test, Generator Current Lagging.

In Fig. 870 it will be noticed that the current O C in the generator lags by the angle ϕ_g behind the generator E.M.F. It is obvious that by altering the relative magnitudes of O G and O M, which can be done by altering the excitation in either case, this angle of lag may be given any value desired, and may even, by over-excitation of the motor and under-excitation of the generator, be made into an angle of lead. This is shown graphically in Fig. 871, in which the vectors are marked as in Fig. 870. By careful adjustment the power factor of the generator can be made unity.

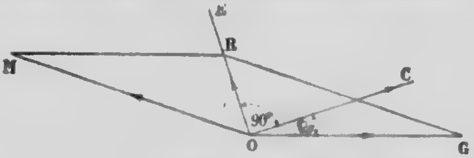

Fig. 871.—Vector Diagram, Hopkinson Test, Generator Current Leading.

The losses are chiefly made good by the continuous-current motor, whose mechanical output for a given input will be known from its efficiency curve. The copper losses in the excitation circuits of the two machines must be added and the total loss thus ascertained. From this and the electrical load on the generator the efficiency can be calculated.

The result of the test referred to above (*see* page 846) was that with an output of 1,362 kw. with a power factor of 0·98 the total loss was 83 kw., thus giving an efficiency of 94·25 per cent.

The flexibility of alternate-current working as compared with continuous-current working is probably nowhere better exemplified than in the possible adaptations of the Hopkinson method to the testing of alternators. The method primarily requires two similar machines mechanically and electrically coupled. With alternators, however, the conditions can be fulfilled within the limits of a single machine, and that in a variety of ways. Many years ago Moody pointed out that if some of the connections of the windings of an alternator armature were reversed and the machine run on short-circuit with the field excited, the current in the reversed coils being driven against the pressure would act as a motor current returning energy to the rotor. It is, however, undesirable thus to interfere with armature connections, and for this and other reasons some variety of the other principal method is preferred in practice. This consists in reversing the polarity of a certain number of the field poles of a multipolar machine, thus reversing the E.M.F.s in the armature conductors when passing these poles. Behrend, who first proposed this method in 1903, suggested dividing the poles into two equal groups, in one of which the exciting current was reversed. This, however, obviously gives unbalanced magnetic pulls on the two halves of the field, so much so that it was quite unsafe to run the machine at anything like full excitation. Other divisions of the field with the same object in view have been proposed, and Dr. S. P. Smith,* who has devoted much attention to this subject, schedules twelve different methods of dividing the field of a twelve-pole machine; four of these give unbalanced fields, of which two are safe, and eight balanced fields, of which two are proved by experiment to be very good and one excellent. The last-named had the coils alternately generator and motor coils in equal numbers. In a more recent paper (1908), Dr. Smith divides the field of a 48-pole machine into thirty generator poles (two groups of eight and two of seven) and eighteen motor poles (two groups of five and two of four).

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* For the meaning of the product of two such vectors *see* Vol. I., page 700

When the above test is made the losses are supplied, as in Fig. 869, by a driving motor whose mechanical output can be ascertained, and to this has to be added the excitation losses if the exciter is not coupled to the shaft of the alternator.

If it be desired to separate the various losses, this can also be readily done, as may be seen from the following example given by Dr. Smith for a 177 kw. machine with coupled exciter. The driving motor absorbed 5·5 kw. when running alone, and 7·0 kw. when running the alternator and exciter light, hence :—

Windage and friction loss = 7·0 − 5·5 = 1·5 kw. (0·9%) . . (1)

When driving the alternator, normally excited on open circuit, the motor absorbed 16·4 kw., of which 2·9 kw. was used in the excitation circuit, hence :—

Alternator iron loss = 16·4 − 2·9 − 7 = 6·5 kw. (3·7%) . . (2)

When driving the alternator on short-circuit under full-load conditions the motor absorbed 21·4 kw., of which 4·3 kw. was used in the excitation circuit, hence :—

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* *The Electrician*, Vol. LV., page 509 (1905).

$$\text{Stator copper loss} = (21{\cdot}4 - 4{\cdot}3) - (16{\cdot}4 - 2{\cdot}9) = 3{\cdot}6 \text{ kw. } (2\%) \quad . \quad (3)$$

$$\text{Full load excitation loss} = 4{\cdot}3 \text{ kw.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$\text{Total loss} = 21{\cdot}4 - 5{\cdot}5 = 15{\cdot}9 \ (8{\cdot}5\ \%)$$

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{177}{177 + 15{\cdot}9} = 91{\cdot}5\%$$

In connection with these tests several interesting problems arise upon which we have not space to enlarge. They chiefly centre round the question as to how far full-load conditions, as regards excitation, heating, iron losses, etc., are reproduced in *all* their details, and how far the assumptions underlying the calculation just given are justifiable in making deductions for full-load conditions. Experienced experimenters assert that by combining temperature observations made after the ordinary "no-load" and "short-circuit" tests it is possible accurately to predetermine the heating on full load when both exciting coils and core are active.

The Hopkinson method of test has also been applied to induction motors, which, as we have shown, can, under certain circumstances, act as generators. The interpretation of the tests gives rise to problems which lack of space makes it impossible to deal with here. Readers who are interested can consult a paper by Dr. S. P. Smith in *The Electrician*, Vol. LXIII., page 165 (19[illegible]).

VII.—RUNNING-DOWN TESTS

The Hopkinson test and its developments furnish direct methods of measuring the total losses of the machines under test, and also, in some cases, allow these losses to be separated with some of their component parts. Another general method of obtaining information from which the losses can, with care, be approximately deduced, is by taking what is known as a "running-down" test. Put briefly, this consists in running the machine under test up to a speed above the normal and disconnecting the apparatus required for this purpose. The test machine is then allowed to run down under definite conditions until it stops, and careful time readings of the speed are taken during the period of deceleration.

For this purpose a stroboscopic method of speed measurement, such as is described on pages 823 to 826, is particularly convenient and Fig. 872 gives some measurements of this kind taken by Dr. Drysdale when experimenting on speed measurements of this kind. In Fig. 872 time is plotted horizontally and speed vertically. The experiments were made on a 3-B.H.P. Langdon-Davies single-phase motor, which was run up to a little above the highest speed recorded in the diagram and then was allowed to run down to rest under the different conditions specified on the curves. The curve on the right with the least slope was obtained with the machine quite unloaded, the decelerating torques being due to [illegible] windage only. For the other three curves a known brake torque as specified was added, the motor pulling up much more rapidly as the brake torque was increased, until with the heaviest load used only 20 seconds were taken to stop dead, and it must have been very difficult with the method adopted to obtain reliable readings to plot the curve.

The theory of the interpretation of such curves is simple, but its application in practice is not quite so easy. When a rotating body is changing its speed we have the elementary equation:

Torque = (moment of inertia) × (angular acceleration) . (1)

consistent units, of course, being used. If the body be slowing down the torque is a retarding torque and the acceleration is negative, that is it is a deceleration, and since the moment of inertia remains unchanged:

Retarding torque $\propto$ angular deceleration . . . . (2)

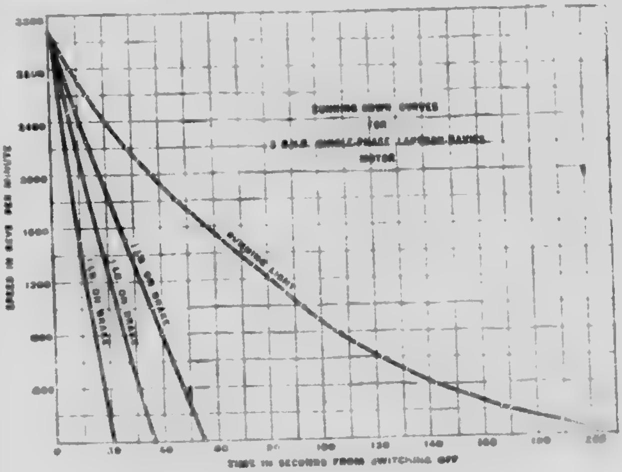


Fig. 872.—Running-down Curves of Small Motor.

Now, in a running-down curve plotted as in Fig. 872, since the angular velocity is plotted against the time, *the rate of change of angular velocity*, which is the angular deceleration, is measured at any point by the slope of the curve at that point. This slope is known if we can draw the tangent T P N (Fig. 873) to the curve at the point P, for the slope is the tangent of the an[illegible] and with proper units we have

Angular deceleration = tan T N O [illegible] . . . (3)

Two difficulties arise in practice. The first is to draw the tangent line T N with sufficient accuracy. The curve A P C not being a known geometrical curve, the drawing of its tangents is a matter of guesswork, and the accuracy of the result depends on the eye of the draughtsman. The usual way is to first draw the curve itself very carefully as a fine line from the plotted observations, and then, taking a fine black thread, stretch it taut and move it about until, passing through P, it seems to be in the right position, that is, taking the real direction of [illegible]. Th[illegible] points T and N, in which it cuts the two axes, can then be read off, and if necessary, the line T N drawn after the thread is removed. It will be obvious that with certain curves high accuracy cannot be ensured.

The second difficulty lies in obtaining the actual value of the torque, which is only proportional, and not equal, to the deceleration so obtained. The multiplying factor (*see* equation (1)) is the moment of inertia, a quantity not easy to determine experimentally.

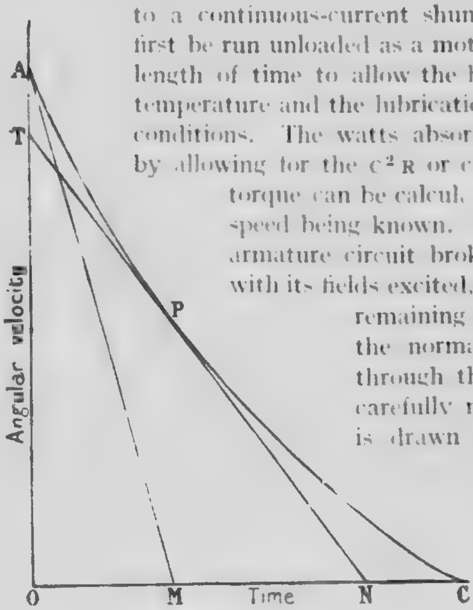


Fig. 873.—Theory of the Running-down Curve.

A simple method of obtaining the necessary experimental data without measuring the moment of inertia directly is the following, as applied to a continuous-current shunt machine. The machine should first be run unloaded as a motor at normal speed for a sufficient length of time to allow the bearings to assume the stationary temperature and the lubrication to settle down to usual running conditions. The watts absorbed at this speed are noted, and by allowing for the C^2R or copper losses, the steady retarding torque can be calculated from the remaining watts, the speed being known. The speed is then raised and the armature circuit broken, when the machine will retard with its fields excited, the armature iron losses therefore remaining as before, when it passes through the normal speed. The time of passing through this normal speed O A (Fig. 873) is carefully noted, and the retardation curve is drawn from that point onwards. The angular deceleration at normal speed is measured by the slope of the curve at A as the ratio of O A to O M, and the retarding torque being known at this speed the multiplier can be deduced, which must be used at the speed denoted by any other point P on the curve to obtain the retarding torque at that speed. From these calculations the speed-torque curve of Fig. 873 can be plotted and the losses analysed.

If the running-down test be repeated with the field circuit broken, as well as the armature circuit, the magnetic losses will disappear and the frictional torques alone will be acting. Data will thus be obtained for determining the hysteresis losses of Fig. 863. If the brushes can be lifted suddenly after the current is switched off a further running-down test will enable the brush friction to be separated.

To secure fairly accurate results in running-down tests, small details must be carefully watched to ensure that the conditions of the test are actually those assumed. The method of testing is not well suited for sepating the losses in alternate-current motors, as a curve such as that given Fig. 873 is not easily interpreted.

A typical retardation curve with a number of the tangent lines drawn given in Fig. 874. It is taken from a paper by Professor Robertson c. *cit.*) and exhibits the results of experiments on a continuous-current machine with the field "off." It will be noticed that the speed runs down from 1,250 R.P.M. to zero in 97·5 seconds. A separate "steady-running" test showed that the net power lost at 1,250 R.P.M. under the conditions of the running-down test was 391 watts, from which the retarding torque at that speed was calculated. It may be of interest to mention that with the field "on," the same motor ran down from normal speed to "stop" in 44·3 seconds.

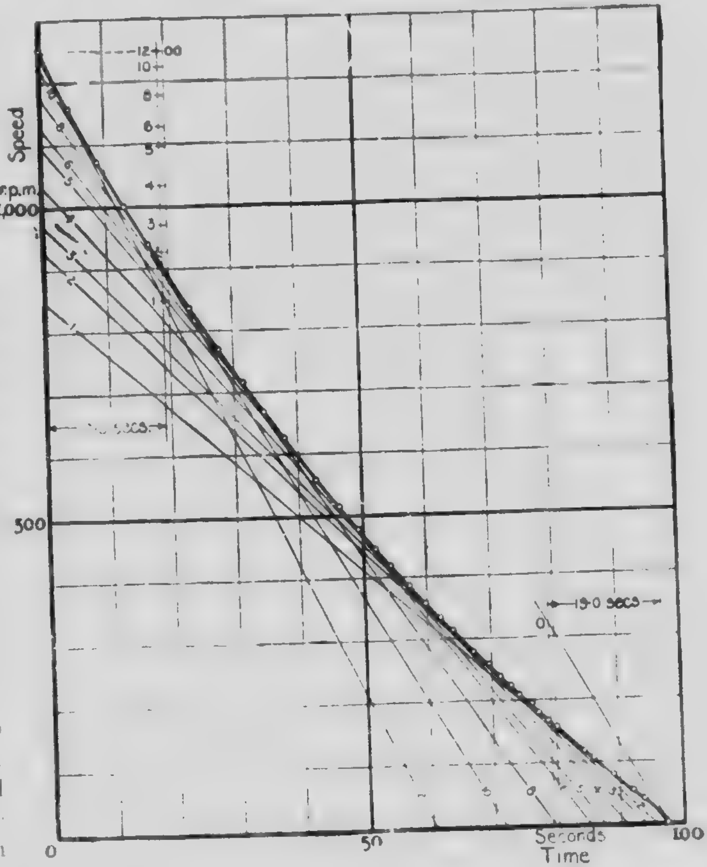


Fig. 874.—Typical Retardation Curve with Tangent Lines.

VIII. HEAT AND OTHER TESTS

Heat Tests.—One of the most important tests to which the purchaser can subject a new machine is the *heat* or *temperature test* at full load. The object of the test is to ascertain the steady temperature above the temperature of the surrounding atmosphere which the machine eventually reaches when run for a sufficiently long time on full load. Now the losses of all kinds due to electric resistance in the conductors, eddy currents, hysteresis, and ordinary mechanical friction eventually appear as heat in the machine. Further, the rate at which the machine loses heat depends, amongst other things, upon the difference of temperature between the machine and its surroundings; the greater this difference of temperature the greater the rate at which the waste heat, which is energy in a useless form, leaves the machine. But as long as the waste energy produced by the machine per minute is greater than the rate at which the machine is losing heat, the temperature will continue to rise, and the rate of loss to increase. When balance is attained the temperature will become steady, and remain steady as long as the conditions are unchanged. The steady excess temperature at full load is therefore a valuable indication of the inefficiency of the machine, though it has not, of course, the same metrical value as direct tests.

The most usual method adopted to ascertain this excess temperature is to run the machine for a sufficient length of time—six hours is frequently specified—at full load. It is then stopped, and the temperatures of the various parts—but more especially of the armature—ascertained. The temperature is usually measured with good thermometers, such as are used in chemical experiments, the bulb of the thermometer being brought into intimate contact with the metal at the point where the temperature is required. A better method, if the instruments are available, is to measure the resistance of the hot armature circuit and compare it with its known resistance when cold. From the increase of resistance and the known temperature coefficient of copper, the rise of temperature can be calculated. The temperature so ascertained will be the mean temperature of the circuit, and not the temperature at one arbitrarily selected spot as with a thermometer test. During the six hours' run the temperature of the testing room should be measured from time to time by a thermometer, placed in a position in which it cannot be directly affected by the heat radiated from the machine.

The excess temperature under the above conditions is largely influenced by the thoroughness of the ventilating arrangements, and by the exposed surfaces of the machine. It can, therefore, as has been said, only be taken as an *indication* of inefficiency. But a machine which keeps moderately cool when running has other advantages, besides being generally more efficient than one of similar pattern which gets hot. It is, therefore, interesting to know that modern dynamos can be obtained which give an excess temperature of not more than 50° F. after a six-hours' run at full load without the machines being made excessively large for their rated power.

With tramway generators and large machines for central station work it is well also to test the temperature effect of a considerable overload—

say of 25 or 50 per cent. for a short period of time, and machines are sometimes built which do not exceed the above-named excess temperature of 50° F. after a two-hours' run at 50 per cent. overload.

A method of applying such a test to a tramcar motor is shown in Fig. 875, which represents under test one of Dick, Kerr and Co.'s motors, already described (*see* pages 630 to 632). The motor, mounted on a frame, has a wheel fixed on to its armature axle, and a rope brake is attached to the wheel and adjusted until it absorbs all the power developed by a full-load current. The brake wheel is kept cool by a supply of water as shown, and the test lasts an hour. At the end of the run the temperature is ascertained by a thermometer, and the condition of the bearings and commutator noted.

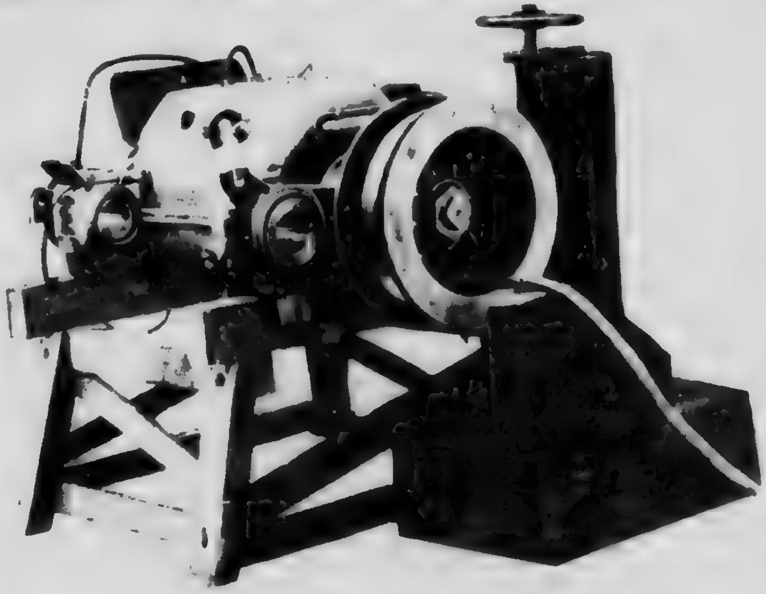
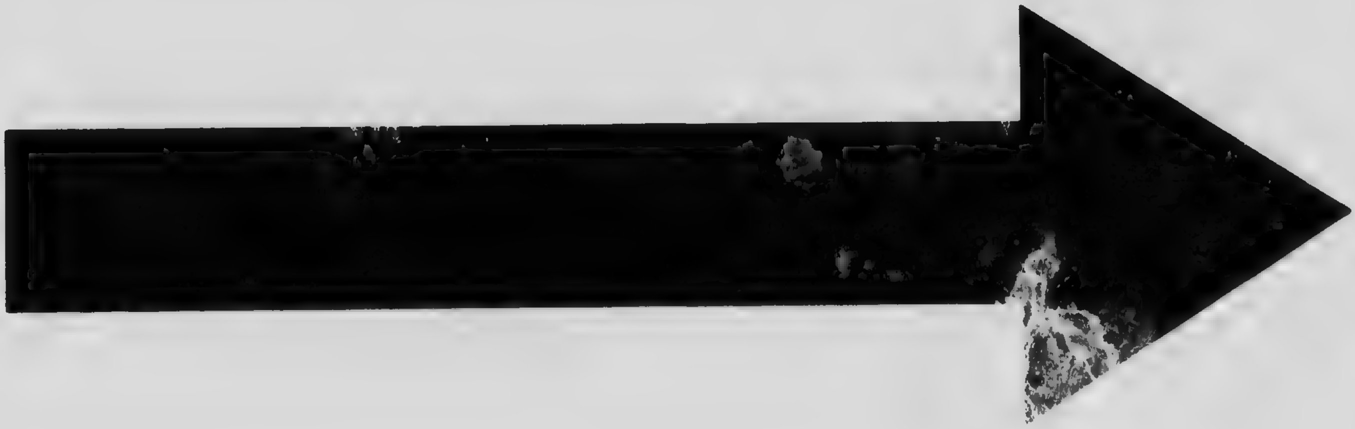


Fig. 875.—Temperature Test of a Tramcar Motor.

With machines such as the one illustrated in Fig. 875 the test can be carried out conveniently and with no great expenditure of energy. But with large machines the difficulties and inconveniences already alluded to more than once in the preceding pages intervene. If it be costly to run a large machine for a short time at full load to complete some of the tests described above it becomes a still more serious matter when it is required to run such a machine of say 1,000 to 20,000 kilowatts output, on full load or on an overload for a long period of time. Any method which promises to give reasonably accurate results without such a large



MICROCOPY RESOLUTION TEST CHART

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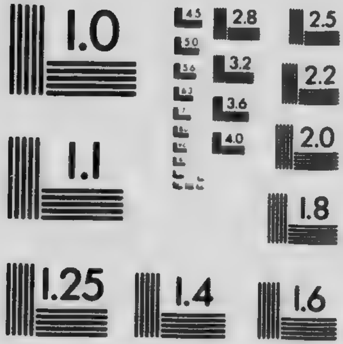

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waste of costly energy is therefore worthy of careful consideration, and more than one such method has been indicated in the preceding pages.

As explained above, and for the reasons given, the rise of temperature of a machine under test is rapid at first, and then slower and slower until the balance referred to is attained. Provided the conditions of the test remain unchanged, the time-temperature curve follows a perfectly definite and well-known law given by the equation

$$\theta = \Theta\ (1 - \epsilon^{-at})$$

where θ is the excess temperature at the time t, Θ is the final excess temperature, a a coefficient to be determined by experiment, and ϵ (= 2·7183) the base of the Napierian logarithms.

In 1911 Dr. S. P. Thompson suggested that this curve could be plotted, or the coefficient a ascertained without continuing the experiment long enough for the final excess temperature Θ to be attained even approximately, and he indicated in Fig. 876 how this could be done. The curve O P Q is the curve given by the above equation, and the initial slope of the curve as shown by the tangent line O T is a measure of the value of the coefficient a, which, as a matter of fact, is numerically equal to the product of the final temperature multiplied by the tangent of the angle T O H as expressed in terms of the scale units used. Calling this tangent the *slope* of the curve at any point, Dr. Thompson pointed out if P be a point on the curve at which the curve has a slope which is half the slope at O the ordinate at P is $\frac{1}{2}\Theta$. If therefore the point P can be accurately determined the final excess temperature Θ will be known, and it is obvious that O H is a very much smaller time than that necessary for the ordinates to reach the line T U V, for which the ordinate is Θ, and which is an asymptote to the curve.

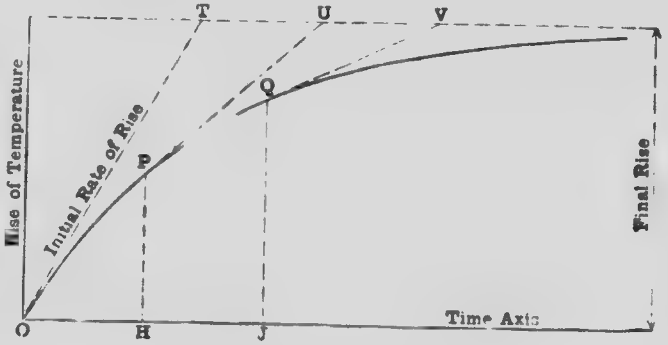

Fig. 876.—Analysis of a Temperature Curve.

As a further check, if a point Q can be found at which the slope of the curve is again halved, that is, a point at which this slope has one-quarter of the value of the slope at O, the ordinate Q J will be three quarters of the final ordinate. The two time intervals O H and H J should also be equal, which gives another graphical check.

More recently the value of Dr. Thompson's suggestion has been tested by various experimenters, and in 1913 Mr. W. R. Cooper published a paper on the subject entitled, "Short Heat Tests on Electrical Machines."* In addition to Dr. Thompson's rules for determining the final temperature from an examination of the early parts of the curve, Mr. Cooper gives other rules derived by easy mathematical processes from the fundamental equation.

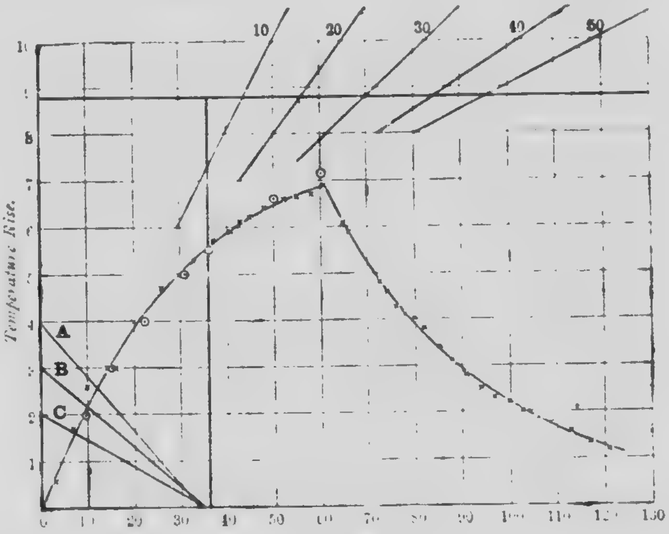

Fig. 877.—Analysis of Heating and Cooling Curve

In an actual machine under load the conditions are not quite so simple as those on which the fundamental equation is based. The production of heat inside the machine is localised in several sections, and the conducting paths by which this heat reaches the final radiating surfaces are very various. The formula takes account of the complications thus introduced, and Mr. Cooper found that at the earlier part of the curve the logarithmic form was not strictly followed. Consequently the quantity $\frac{1}{a}$ is more accurately obtainable from the cooling curve, which follows the same logarithmic law, than from the heating curve. This quantity $\frac{1}{a}$, which, if known, fixes the curve, is, on reference to the equation, obviously a time, and he proposes to call it the "thermal time constant." It is that time in which the ordinate of the heating curve, if the curve be strictly logarithmic in shape, would rise to 63 per cent. of the final value of the excess temperature, and also the time during which, starting from any ordinate on the cooling curve, a subsequent ordinate sinks to 37 (100 − 63) per cent. of this starting value.

The heating and cooling curves for a 5-kilowatt continuous-current machine experimented on by Mr. Cooper are given in Fig. 877. The observed points are marked by crosses, and the position of the logarithmic curve nearest to the heating curve is denoted by points marked ⊙. The mo [illegible] bable value of the time consta [illegible] was found to be a little over [illegible] e minutes ; its position is indicated by a thickened vertical line. [illegible] e deduced for the final temperature, 8·8, is indicated by a thickened [illegible] al line, and the productions of the tangents drawn at the ends of the ordinates 10, 20, 30, etc., are shown in the upper part of the diagram. A, B and C are lines parallel to similar tangents on the cooling curve. The subject would appear to be worthy of further experimental examination.

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* *The Electrician*, Vol. LXXI., page 672, September 19th, 1913.

Direct Measurement of Heat Loss.—It is obvious that if the heat generated as a result of the various losses which cause the inefficiency of the machine can be directly measured, together with *either* the output or the input, the efficiency of the machine can be ascertained. The direct measurement quantities of heat is not easy, but the above problem has been recently attacked successfully by Drs. Barclay and S. P. Smith for the case of turbo-alternators provided with forced ventilation. Measurement of the quantity of cooling air passing per unit time through the machine, and its rise of temperature, gives the data for calculating the rate at which heat energy is being carried off by the air stream; and when the steady temperature state has been obtained for a particular load, this will also give the rate of production of heat within the machine, proper corrections being made for loss of heat by direct radiation.

A similar method was used some years ago, under more difficult conditions, by Prof. Threlfall for machines not provided with ventilating arrangements and, therefore, more difficult to experiment upon.

Self-regulation.—Another important test for the purchaser of machines which are supposed to be self-regulating is the limits between which the self-regulation acts. For instance, if the machine is a dynamo compound wound for constant P.D. at a normal speed, its characteristic curve should be obtained at that speed, and will show the efficiency of the regulation. But in addition the effect of sudden changes of load, both up and down, should be tried. Such changes of load will probably try the efficiency of the governor of the engine more than the self-regulating power of the dynamo, but they should be made nevertheless. In the case of a motor supposed to be self-regulating for constant speed at all loads, the effect of changes of load can be more legitimately tried. With polyphase and synchronous motors the speed measuring arrangements will often have to be very sensitive to detect the changes.

CHAPTER VII

STATIC TRANSFORMERS

The importance of the fact that it is possible to transform economically electrical power of any kind which is of value in engineering work into any other kind of electrical power suitable for practical engineering applications has been referred to frequently in the preceding pages. It is this fact, as pointed out in Chapter XV. of Vol. I., which makes electric systems for the transmission of power much more flexible when long distances are involved than any other system in their adaptation to the widely varying needs of mankind, whether industrial or other. The actual transformations from one kind of electrical power to another can usually be made with only a small percentage loss of the energy transformed wherever large quantities of power are handled, and thus the all-pervading element of cost which runs through and controls successful engineering work can be satisfactorily dealt with. With small quantities of power, down to the minute amounts dealt with in telephony and telegraphy, the cost of wasted energy sinks into insignificance, and questions of convenience and over-all efficiency are paramount. But whether it be the handling of the power of a large waterfall, such as Niagara, or of the minute energy of a sound wave, flexibility and ready adaptation of means to ends are the outstanding characteristics of electrical methods of transformation of power and energy.

I.—CLASSIFICATION OF TRANSFORMERS

An examination of the various types of transformers available and widely used in engineering work, as summarised in Vol. I. (*see* page 575), shows that for convenience of treatment they may be divided into two great classes, according as to whether they have or have not moving parts. In addition there are other types of transforming apparatus to which the term transformer is not usually applied, but which should be included in a general classification, which may be set out as follows:—

(i.) Static transformers,
(ii.) Kinetic transformers,
(iii.) Secondary batteries,
(iv.) Rectifiers.

The "history" of Classes (i.) and (ii.) and the principles upon which they are based have been dealt with in Vol. I. (*see* pages 433 and 628 *et seq.*); this chapter is devoted to Class (i.) only.

Static transformers, as already explained fully in the preceding volume (*loc. cit.*) are simply Faraday induction coils, in which, since the primary is supplied with an alternate current, no break circuit arrangement is required as in the early designs of Bachhoffner, Ruhmkorff, and others. The principles, first discovered by Faraday, have been employed in an almost infinite variety of ways, but in this section we are concerned with those applications of it which handle engineering quantities of power. The smaller apparatus, designed on the same principles and developed for special purposes, will be more appropriately described in connection with those purposes.

As the principles involved have been already explained and historical examples of their application fully described, we follow the plan already adopted for alternators and motors by commencing, after a preparatory classification, with a description of a few modern examples, during which some of the more purely technical points are referred to. In subsequent sections other points of technical and theoretical interest are considered so far as the space available permits.

II.—CLASSIFICATION OF STATIC TRANSFORMERS

Though the conditions are much simpler than they are for alternators and motors, it is found that a simple and exhaustive classification is again not possible, and that any particular classification must depend on the point of view, whether of design or utilisation, deemed most important for the special purpose for which the classification is required. The following are therefore more or less cross classifications:

Magnetic Circuit.—From the point of view of the designer this is probably the most important basis of classification. In the early days of their development transformers were quite conveniently classified magnetically into "open-circuit" and "closed-circuit" transformers, and this method of classification was therefore adopted and fully explained and illustrated in Vol. I. (pages 436 to 442). Except, however, in very special circumstances, and chiefly for the reasons already given, the first type has ceased to be used in engineering work, and modern transformers are practically all of the "closed circuit" type. Within this type there are two main divisions, namely:

(i.) Shell type.
(ii.) Core type.

In the first of these, illustrated diagrammatically in Fig. 878, the iron forms a "shell" round the copper windings, and the examples of closed-circuit transformers described in Vol. I. were of this type.

Except for the ends of the windings (see Fig. 401, Vol. I.), the copper coils, shown in section at E N and H N, are completely imbedded in the

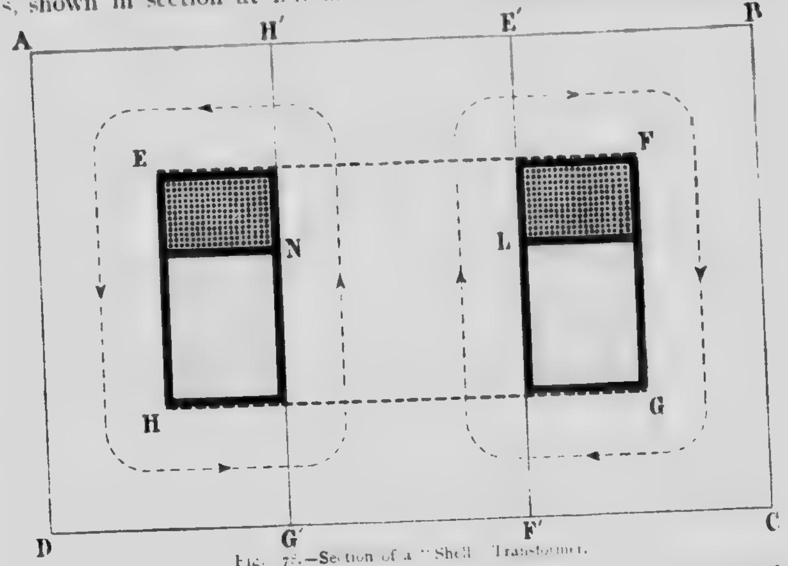

Fig. 878.—Section of a "Shell" Transformer.

iron. The magnetic circuit consists of two paths in parallel, as shown by the dotted lines, the central core being common to both paths.

In the second or "core" type the positions of iron and copper are reversed, the copper now enclosing the iron, as depicted in Fig. 879, except for the end paths of the latter. There is a single magnetic circuit, as shown by the dotted line, and the current carrying coils E N and N′ H are magnetically in series on the two iron cores.

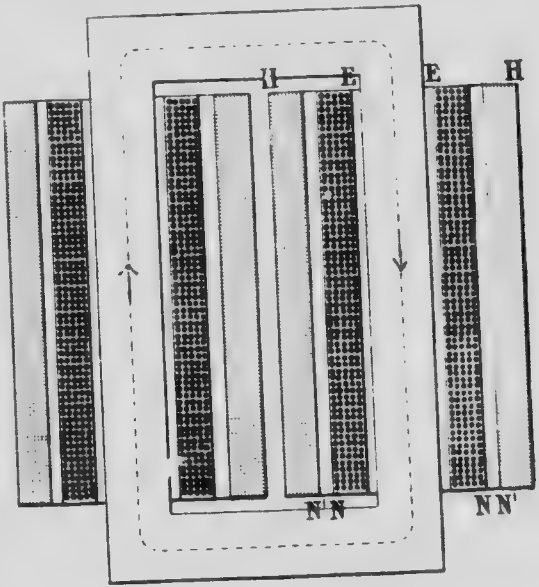

Fig. 879.—Section of a "Core" Transformer.

The first of these types is usually adopted for large outputs and high voltages, and has the advantage that the mean path of the flux for a given rating being less there is a slight saving in iron. The "core" type has the advantages of simplicity of construction and ease of assembling, and with the windings shown in Fig. 879 is more easily insulated.

Electric Circuits. An inspection of Figs. 878 and 879 will show that it is possible to arrange the windings relatively to one another in two different ways, which may be referred to as:

(i.) Sandwich windings,
(ii.) Concentric windings.

The first type is more fully developed in Figs. 880 and 881, which deal with more modern arrangements and far larger transformers than Fig. 878. In these diagrams the position of the iron is indicated, only without the complete circuit being drawn, and only one section of each coil is given. The coils are alternatively low- and high-voltage[*] coils, the total cross-section of each class of windings being approximately the same. In Fig. 880 the number of coils of each kind is the same, but in Fig. 881 the top and bottom coils are both low-voltage coils of half the cross-section of the other coils "sandwiched" between them. In concentric winding it is also possible to split the two windings in the same way. For instance, in

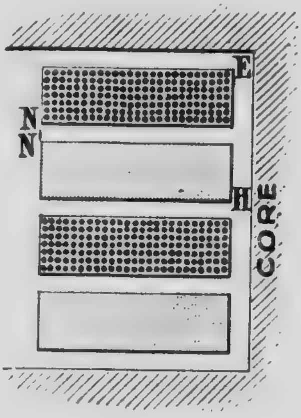

Fig. 880.

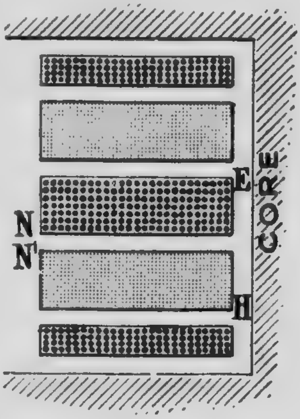

Fig. 881.

Examples of Sandwich Windings

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[*] In the following pages the finer winding of many turns will be referred to as the "high-voltage" winding, and the coarser winding of fewer turns will be called the "low-voltage" winding. The terms at present in common use—namely, "high tension" and "low tension"—are distinctly objectionable, as the word "tension" has connotations which are quite inapplicable. For similar, though not so strong, reasons the word "pressure" used in Vol. I. has been discarded. As transformers may be used either as "step-up" or "step-down" transformers operating on the voltage, the terms "primary" and "secondary," frequently employed in connection with induction coils for the high- and low-voltage coils respectively, cease to have a distinctive meaning in general descriptions.

Fig. 879, instead of the whole of the low-voltage winding being nearest the core, it is quite a usual practice to place half the low-voltage windings next to the core, then the whole of the high-voltage windings and the remainder of the low-voltage windings surrounding all. The advantage of thus splitting the low-voltage windings is that the inductive action of the two circuits on one another is improved or, to put it in the usual way, the "leakage" is diminished.

The chief magnetic difference between the two types of winding is in this matter of "leakage," which, with ordinary concentric windings, varies from 4 to 5 per cent., and with split low-voltage concentric windings may be as low as 2·5 per cent. With sandwich windings the leakage varies almost inversely as the amount of subdivision, and it is one of the advantages of the type that almost any desired leakage from 1·5 to 25 per cent. can be obtained. Great leakage is useful where the transformer is required to act not only as a transformer, but as a reactance or choking coil, as for instance, in stepping down a high-voltage current to feed rotary converters. It is also advantageous as a safeguard against the disastrous consequences of a short circuit in large transformers, inasmuch as it limits the short-circuit current, and with it the dangerous mechanical stresses on the transformer coils, to which allusion is made later. Another advantage of the sandwich type is the greater facility which it offers for effective coil-clamping devices.

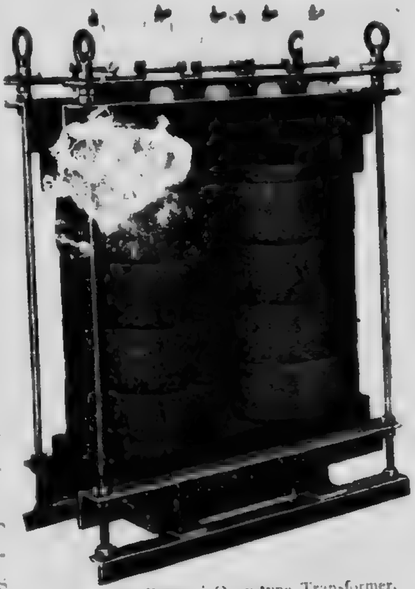

Fig. 882.—Ferranti Open-type Transformer.

On the other hand, the concentric type has the advantages of a cheap and simple winding with leakage reduced to a low limit with consequential advantages in working to which reference is also made later. The effective insulation of the high-voltage from the low-voltage windings is also more cheaply attained, and with the high-voltage winding on the outside lighter insulation can be used between the core and the windings. The greater facility for cooling obtained in the latter case for the high-voltage coil is also of importance, since because of the lower "space factor" of such a winding the current density in the copper has to be greater than in the low-voltage

Fig 883.—Ferranti Semi-enclosed Transformer.

winding if reasonable limits of volume are to be attained. The same conditions which give rise to the lower space factor also make for lower thermal conductivity, hence the importance of providing all possible cooling facilities.

Cooling.—A third method of classifying static transformers is based upon the provision made for keeping down the temperature of the transformer when working under load. The question of the necessity for efficient cooling is dealt with more fully elsewhere, and it need only be remarked here that all the energy lost in transformation appears in the form of heat, which must be dissipated if the transformer is not to become dangerously hot. These considerations lead to the following additional classification, according as the transformer is—

- (i.) Air-cooled by ordinary radiation.
  - (*a*) Open type.
  - (*b*) Semi-enclosed type.
  - (*c*) Totally enclosed type.
- (ii.) Oil-immersed (ordinary radiation).
- (iii.) Oil-immersed and water-cooled.
- (iv.) Cooled by air-blast.

Class (i.) includes all transformers in which there are no special cooling facilities provided, except such modifications of the details of the design as will promote ordinary radiation and the conduction of the heat generated to the radiating surfaces. This class divides into the three types specified according to the amount of mechanical protection necessitated by the special conditions under which the transformer is to be used. The three types are illustrated in Figs. 882 to 884, which are external views of otherwise nearly similar Ferranti transformers. Fig. 882 represents the "open" type for use where no special mechanical protection is required; this type, which was at one time quite general, is now seldom used. Fig. 883 shows the "Semi-enclosed" type in which the transformer is protected from mechanical injury by being surrounded by an expanded iron case through the meshes of which the air can circulate freely to carry off the heat from the transformer. The terminals at the top are more substantially covered in, and the leads are brought out loosely through bushings shown near the top. Fig. 884 shows the "totally-enclosed" type in which the transformer is enclosed in a case which is absolutely oil- and water-tight, and also weather-proof. It is to be used when the transformer has to be placed in damp or exposed situations; and the enclosing vessel is in modern transformers usually filled with oil, in which case the transformer will fall into Class (ii.).

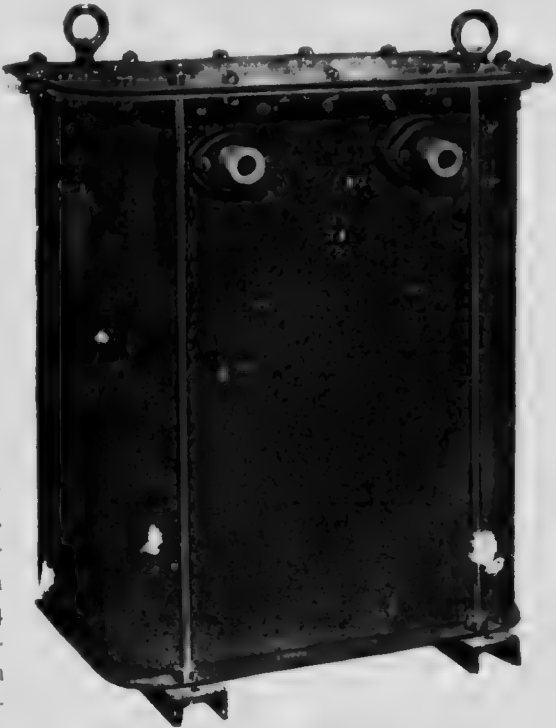

Fig. 884.—Ferranti Totally-enclosed Transformer.

The other three classes will be specifically dealt with in subsequent sections in connection with particular transformers.

III.—MODERN STATIC TRANSFORMERS.

Following the plan adopted in dealing with modern alternators, this section will be devoted to a few illustrations of modern static transformers as a preliminary to the consideration of details, practical and theoretical, which will be taken up in subsequent sections. For this purpose the last classification set forth in the preceding section will be the most convenient, though not exclusively so.

The selection of examples to illustrate modern alternate current or static transformers is attended with as great a difficulty as in the cases of generators and motors, because of the large number of excellent transformers available. We must therefore repeat what we have said in the other cases that the omission of the productions of a particular manufacturer does not imply that they are in any way inferior to the transformers actually described. Where there are so many good examples, it is only possible to describe a small fraction of them, the selection being based upon the desirability of mentioning as great a variety as space permits.

Fig. [illegible]5.—Johnson and Phillips 400 *kv.a.* Single phase Air-cooled Core Transformers.

Air-cooled or Self-cooled Transformers. — This type includes all transformers in which no special facilities are provided, except in details of design, for radiating the waste heat of the transformer under load. For *power transmission* purposes, the transformers used are either single-phase or three-phase. Single-phase transformers in sets of three are, however, largely used on three-phase lines, and may therefore be taken separately as a class [illegible] widely used than their name implies. In many cases further details of the transformers illustrated in this section will be found in the subsequent pages.

Single-phase Transformers.—A set of four single-phase transformers as manufactured by Messrs. Johnson and Phillips, is shown in Fig. 885. The transformers have been removed from their cases, which appear behind, in which they are immersed in insulating oil when in use. The cases are constructed with corrugations to radiate the waste heat in order to keep down the temperature of the loaded transformer; and the chief function of the oil is, by the circulation set up by convection currents, to transfer this heat to the case as quickly as possible. Each of the transformers shown has a capacity of 400 *kv.a.* at 60 periods. The terminals are brought to porcelain insulators, there being two for the high-voltage winding, for which in this case the voltage is 10,000 volts, and four on the low-voltage winding, which is wound for a voltage of 3,300 volts. The two extra terminals are tappings for special purposes, and each increases the cost of the transformer by 0·5 per cent., the change of voltage being ± 5 per cent. The transformers shown are "core" transformers, and the set is a three-phase group with one spare. These transformers have been built for voltages up to 20,000, and the same type would be used up to 33,000 volts.

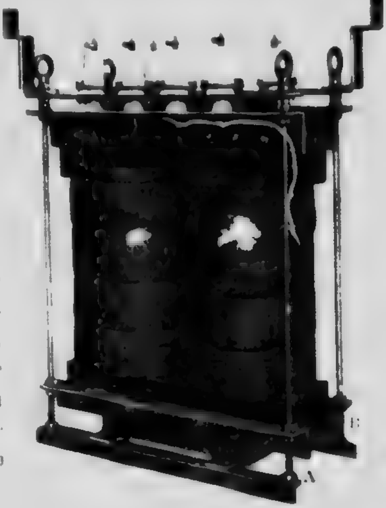

Fig. 886.—Standard Single-phase Ferranti Transformer without its Tank.

The standard single-phase core transformer manufactured by Messrs. Ferranti, Limited, is shown in Fig. 886. It is very similar to the one just described, though there are differences in details to which allusion is made later. The transformer is intended to be supported in an oil-filled case by the angle-irons shown at A and B.

These transformers may be regarded as typical of modern construction of "core" transformers for single-phase working. Concentric windings are very generally adopted, and in most cases the transformers are oil insulated and air cooled, as in these instances.

An example of a single-phase "shell" transformer, with its case, is given in Figs. 887 and 888, which illustrate a standard type manufactured by the British Westinghouse Electric and Manufacturing Company. The standard sizes in which these transformers are made range from 75 to 1,000 *kv.a.*, and they are standard for voltages up to 24,000 volts at any of the usual

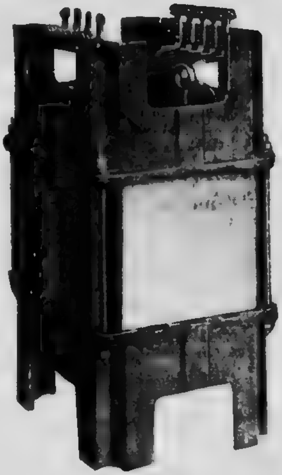

Fig 557.

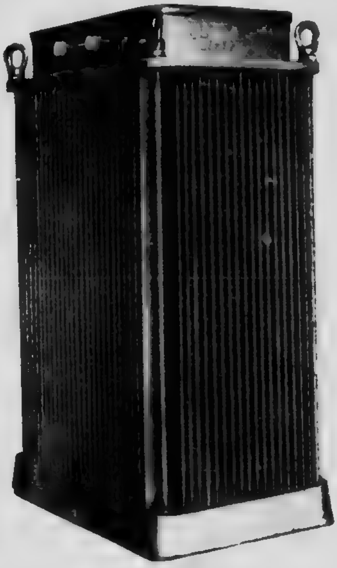

Fig. 558

Standard Westinghouse Oil-insulated Air cooled Shell Transformer.

frequencies. As can be seen from the terminals, tappings can be provided on either the high-voltage or the low-voltage side. In the smallest size, 75 *k*v.a., the weight of the transformer is about 1,150 lb., that of the tank 840 lb., and that of the oil 900 lb., so that the working weight is about 2,900 lb., or rather over 1¼ tons. For the high-voltage 500 *k*v.a. size the weights are 3,750 lb., 2,050 lb. and 2,800 lb. for transformer, tank, and oil respectively, giving a total weight of 8,600 lb., or about 3·8 tons, being about three times the weight for an increase to 6⅔ times in the output.

The Berry single phase transformer manufactured by the British Electric Transformer Company, Limited,

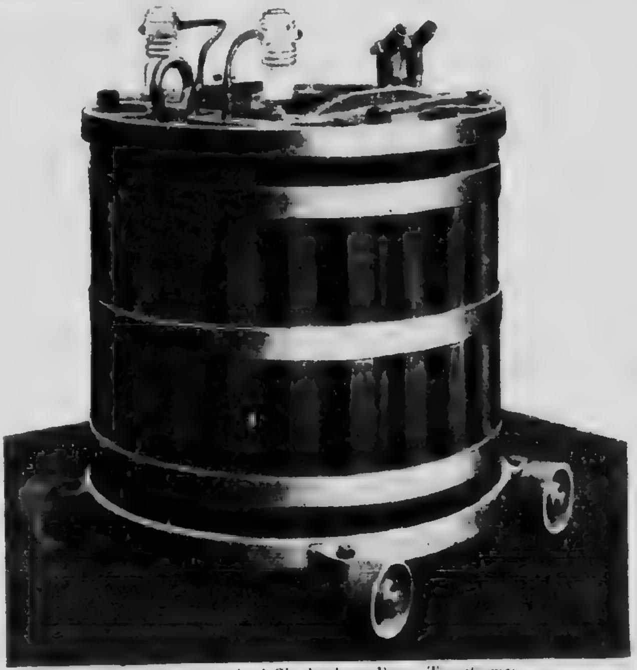

Fig. 559.—Standard Singlephase Berry Transformer.

differs considerably in appearance from any of the foregoing, as will be evident by an inspection of Fig. 889, taken from a photograph of a 200-*k*V.A. air-cooled transformer. The laminated iron seen projecting radially outwards is the iron of the yoke. The copper windings are in horizontal coils round the vertical axis. Further details are given later (*see* page 886). The particular transformer shown is mounted on rollers, and has an output of 500 *k*V.A. at 50 periods. Its weight is about 5 tons and its over-all size is 45 inches square in plan and 64 inches high. Like the transformers first described above, it can be placed in an oil tank to facilitate cooling.

The above show fairly well the present English practice in ordinary single-phase transformer construction; for comparison Fig. 890 gives a view of the present standard type (Type H) of small transformer, manufactured by the General Electric Company of Schenectady, N.Y. It is not entirely either a shell or a core transformer, since the coils are more exposed than in the usual shell transformer (*cf.* Fig. 887), and the iron of the magnetic circuit is more exposed than in a core transformer (*cf.* Fig. 886). Standard sizes range from 1 to 100 *k*V.A. at 60 periods, with the high-voltage side wound for 2,200 or 2,400 volts, and the low-voltage side for 110, 120, 220, or 240 volts as standard voltages. The transformer in its case, but with the cover removed, is shown in Fig. 891, an external view of the complete transformer being given in Fig. 892. The net weight of the transformer, including the oil, in which each size is immersed, ranges from 120 lb. for the 1-*k*V.A. size to 2,785 lb. for the 100-*k*V.A. size, the weight of the 75-*k*V.A. size being 2,430 lb. It is interesting to note that the difference

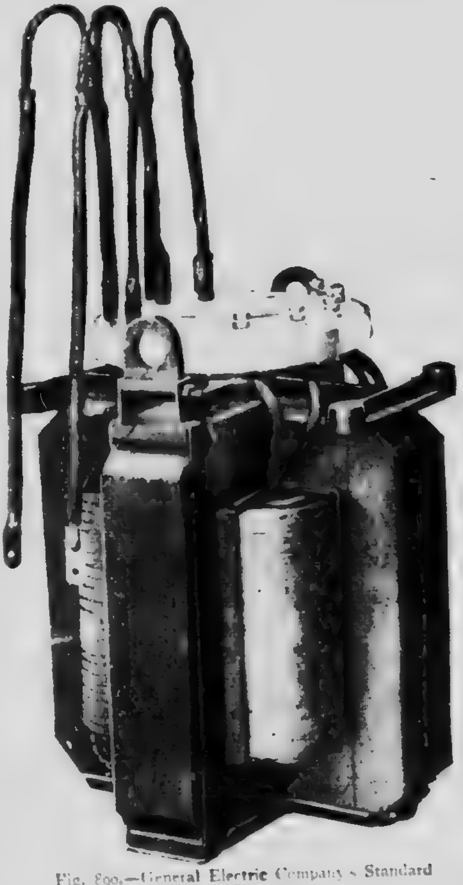

Fig. 890.—General Electric Company's Standard (H-Type) Transformer.

between this weight and the weight of the 75-*k*V.A. transformer previously given is nearly all accounted for in the smaller quantity of oil used, which is 540 lb. as against 900 lb. in the previous case. The other transformer was also wound for much higher voltages, which would somewhat increase the weight.

Three-phase Transformers.—As already remarked, transformers for three-phase currents frequently consist of three single-phase transformers banked together with their primaries and secondaries connected in "star" or "mesh," or in any other way required by the exigencies of the service.

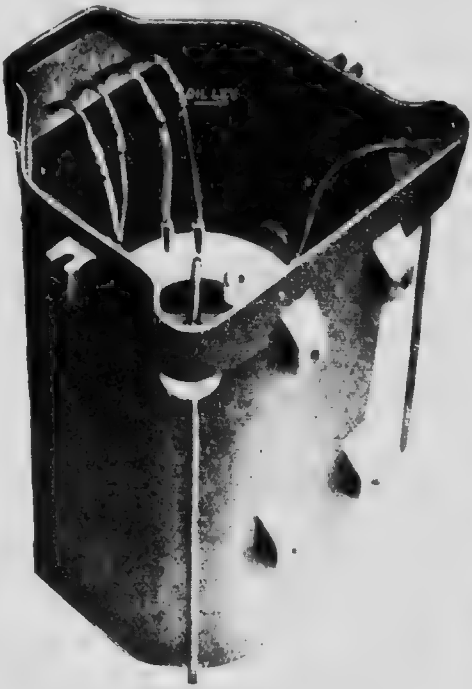

Fig. 891.—G.E. Transformer in Tank with Cover Removed.

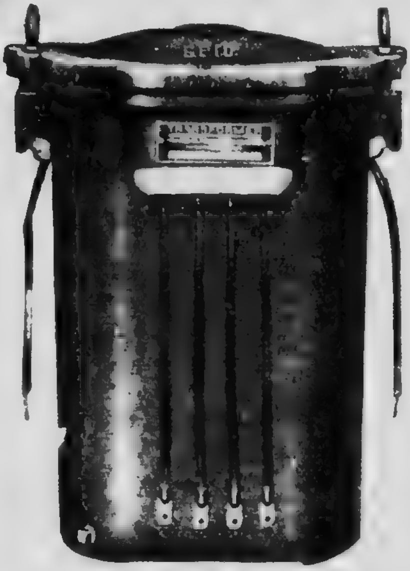

Fig. 892.—Complete G.E. Standard Transformer in Tank.

Quite a number of three-phase transformers are, however, specifically designed as single pieces of apparatus for three-phase work. Thus, Fig. 893 shows without its tank the standard three-phase core transformer manufactured by Messrs. Johnson and Phillips. These transformers are manufactured in standard sizes from 5 to 750 *k*V.A., and for standard periodicities of 25, 40, 50 and 60 cycles per second. The 75-*k*V.A. size at 50 cycles weighs 1,215 lb. net, or with its tank 2,160 lb. gross, or rather less than one ton. The high-voltage limits are 6,000 in mesh or 10,000 in star.

The standard type of three-phase transformer manufactured by Messrs. Ferranti, Limited, is shown in Fig. 894. The details of this transformer (*see* pages 905, 918 and elsewhere), which is of the most recent design, are fully described in subsequent sections. The figure shows the side upon which the high-voltage leads are brought out, and it will be noticed that on each limb there are several tappings carried to special terminals, which are described later. These leads are kept in place by being passed through porcelain bushings in the flange of the rolled channel steel, which forms part of the clamping framework. When in its oil vessel the level of the oil rests above the tops of the terminals shown in the figure. The transformer illustrated has an output of 200 *kv.a.* at 50 periods, the voltages being 5,000 and 355 volts with both sides "star" connected, or 5,000 and 205 when the high-voltage is "star" and the low-voltage is "mesh" connected.

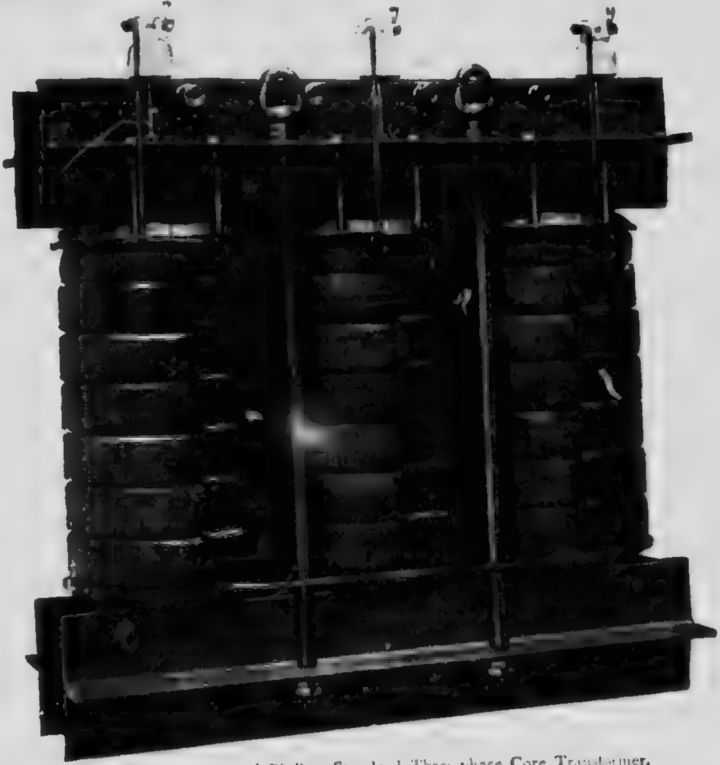

Fig. 893.—Johnson and Phillips Standard Three-phase Core Transformer.

For comparison, both as regards points of resemblances and differences, Fig. 895 shows the standard type of transformer manufactured by the Brush Electrical Engineering Company. The transformer illustrated is a 900-*kv.a.* transformer, of which the over-all dimensions are—length 68 inches, width 28 inches, and height 56 inches over the transformer itself, and 97 inches to the top of the eyebolts shown in the figure. The vertical distance between the top of the transformer and the terminal board is thus proportionately much greater than in the Ferranti transformer (Fig. 894), the object being to utilise a greater quantity of oil for cooling purposes, a subject which is dealt with in a subsequent section (*see* pages 915 to 928). The terminal board is well supported above the transformer, and the eyebolts used for lifting the transformer out of its tank are attached to long vertical rods which pass down and are securely attached by nuts and lock-nuts to the flanges of the channel irons which clamp the upper yoke stampings.

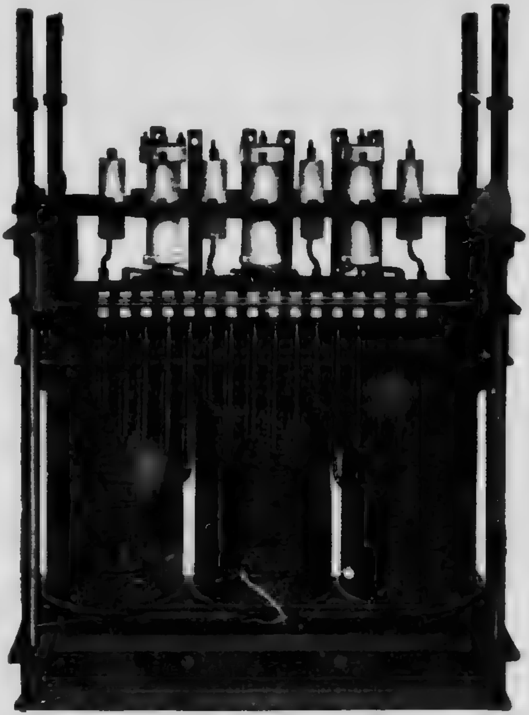
Fig. 894.—Ferranti Standard Three-phase Transformer.

The circuits of the transformer are connected to the terminal board by the numerous leads seen in Fig. 895, which shows the side on which the low-voltage leads are carried up, whereas Fig. 894 shows the high-voltage leads of the Ferranti transformer. Further particulars of these leads and their insulation are given in the section on the electric circuits (*see* pages 886 to 899). The voltage transformation is from 12,000 to 2,750 volts at 50 periods.

The total weight of this transformer without tank and oil is 8,400 lb. (over 3½ tons), of which 4,500 lb. is the weight of the core and 1,700 lb. the weight of the copper. The total weight complete in its tank (Fig. 940) when filled with oil and in working trim is 20,500 lb. (over 9 tons), the volume of the oil being 750 gals. and its weight about 6,400 lb., or nearly 3 tons. The efficiency at full load is 98·66 per cent., the temperature rise after a long full-load run being 40° C.

For mounting on poles in overhead transmission systems, which is only possible with small transformers, the three-phase transformer is obviously more suitable than three single-phase transformers. For this purpose the British Westinghouse Company manufactures in sizes from 1 to 15 *k*v.a. the three-phase transformer shown in Fig. 896, without its oil tank, but including the tank cover, to which are cast the supporting lugs L L for mounting it on a pole or a wall. The leads are brought out at each end of the cover through porcelain bushes, the joint being made quite watertight. The ends of the cover extend over the ends of the tank, and form cowls protecting the outgoing leads from rain. The 10-*k*v.a. size (50 $\sim$) weighs 750 lb. when complete with tank and oil. It is 32 inches long, 14 inches from back to front, and 26 inches high.

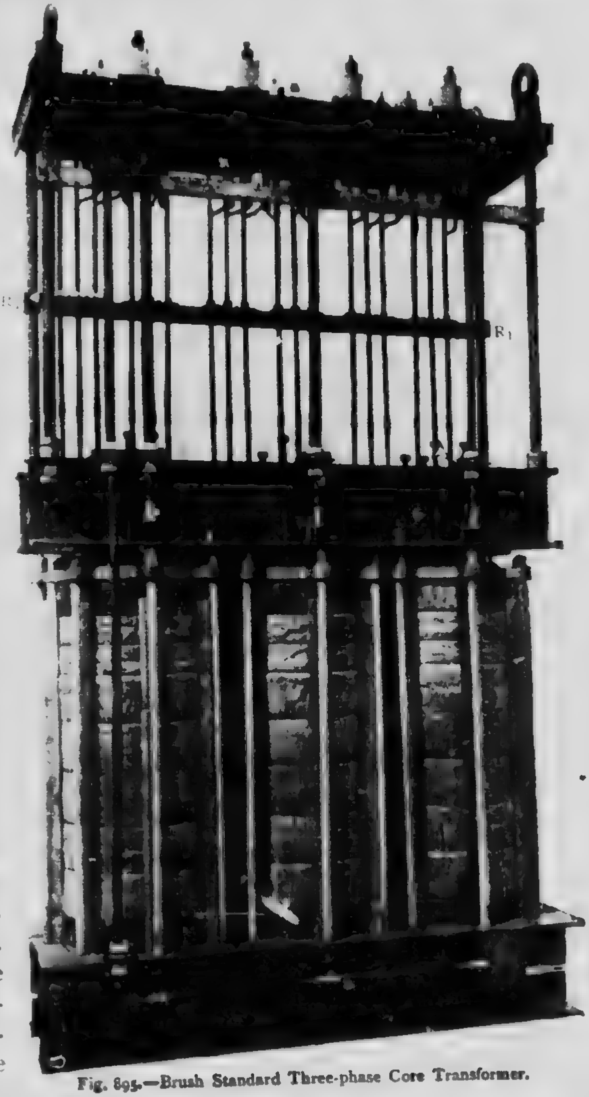

Fig. 895.—Brush Standard Three-phase Core Transformer.

Another three-phase transformer designed for mounting on poles is shown in Fig. 897. These transformers are used by the Government in the hydro-electric power scheme at Lake Coleridge, N.Z. The output is 29·5 *k*v.a., or 25 kilowatts at 0·85 power factor at 50 periods. The supply voltage is 10,000 volts, and the original specification was for a "mesh-star" combination with the neutral brought out on the

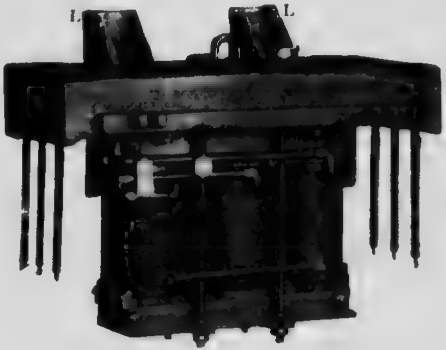

Fig. 896.—Westinghouse Standard Three-phase Transformer for Pole Service.

low-voltage side. This enables a voltage of 400 volts to be used for power purposes and 230 volts from any one phase to the neutral to be used for lighting. Eventually the "star-zigzag" combination was adopted for reasons given below (*see* p. 943), where the "zigzag" connection is described.

The high-voltage leads are brought out through porcelain bushings, protected from the weather at the ends of the transformer, two at one end and one at the other. The four low-voltage leads are similarly brought out in front.

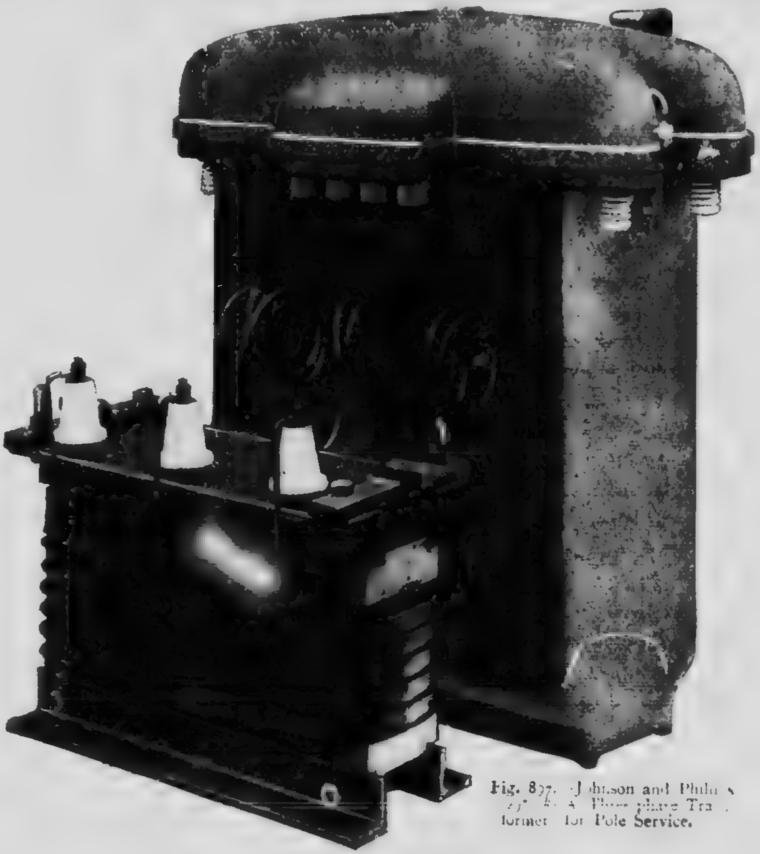

Fig. 897.—Johnson and Phillips [illegible] Three-phase Transformer for Pole Service.

The transformer without its case stands 21¼ in. high to the top of the insulators, and is 26 in. long by 11 in. wide over all. Complete in tank the extreme dimensions are 44 in. high, 30 in. long (including the overhanging eaves at the ends), and 18½ in. deep from front to back (again including the overhanging eaves). The temperature rise allowed was exceptionally low; hence the excessive height of the tank for so small a transformer, the object being to use a large quantity of oil. The tank shown holds 38 gallons of oil, and when the transformer was tested it showed a rise of only 35½° Centigrade after a long continuous full-load run. The weight of the transformer complete in tank and including the oil is 1,334 lb., or say, 12 cwt. Two rectangular hooked straps, the top of one of which can be seen in Fig. 897, are provided for hanging the transformer from the pole cross-arm.

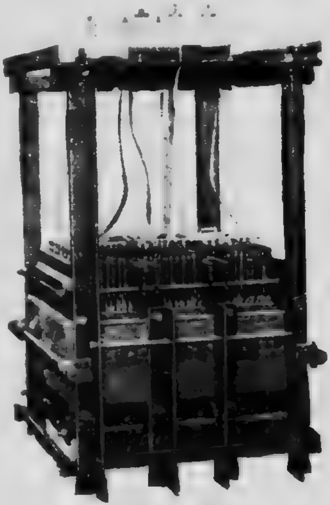

Fig. 898.—Siemens Three-phase "Shell" Transformer.

The above three-phase transformers are of the "core" type. In Fig. 898 there is illustrated a "shell" type three-phase transformer as manufactured for large outputs by Messrs. Siemens Brothers Dynamo Works, Limited. This particular transformer has an output of 625 *k*V.A., at 50 periods per second, the voltage ratio being 11,000 to 520 volts. The weight of the transformer with its oil tank is 3·96 tons, the weight of oil required being 2·45 tons, so that the total weight of the transformer ready for load is 6·41 tons. Further references are made to this transformer later.

The Berry three-phase transformer of the British Electric Transformer Company, which, as we explain elsewhere, is practically a "shell" transformer, is built up very simply of three single-phase transformers placed one over the other, as in Fig. 899, forming one long cylinder with the leads brought out to a terminal board on the top of the uppermost. The particular transformer illustrated has an output of 1,125 *k*V.A. at 50 periods, the voltages being 20,000 and 1,000 volts. Without its tank it weighs 9,400 lb., and with tank and oil complete 16,000 lb. At full load the temperature rise is not to exceed 55° C.

IV.—THE MAGNETIC CIRCUIT

The principles underlying the design of a good magnetic circuit where economy of excitation is a desideratum have been fully explained in the preceding chapters and need not be dwelt upon in detail here. In the static transformer the problems encountered are not nearly so complicated as in the magnetic circuits of generators and motors, in which the conditions interpose in the circuit a more or less wide non-magnetic gap. Though considerations of economical construction make it impossible to avoid a non-magnetic break in the magnetic circuit of a power transformer, the break is of the nature of a bad joint whose reluctance can be reduced to a minimum, and not of the nature of a gap in the ordinary sense of the word.

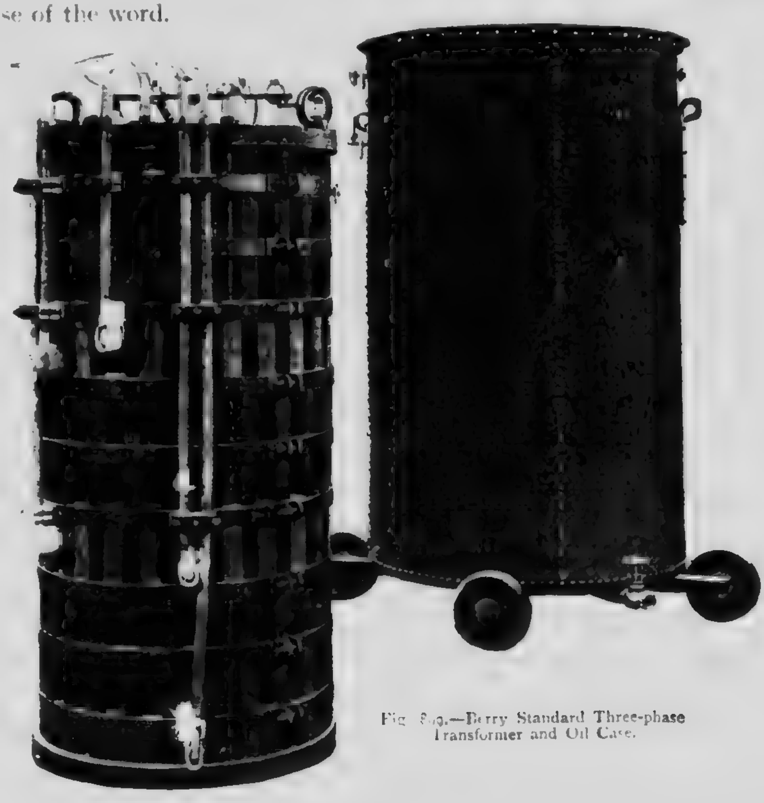

Fig. 849.—Berry Standard Three-phase Transformer and Oil Case.

Laminations.—The iron is necessarily laminated parallel to the flux for the reasons given in connection with the lamination of the cores of dynamo machines (*see* page 490, Vol. I.), and as iron wires or infinitely thin iron plates are mechanically and commercially ruled out, it only remains to determine the economical thickness of the iron stampings at which the losses from eddy currents are counterbalanced by advantages in other directions. Practice places this thickness at from 14 to 18 mils (0·014 to 0·018 inch).

Materials.—The properties of good magnetic iron and low-carbon steel have also been dealt with in connection with dynamo design (*see* pages 52 to 55). In transformer design the iron and copper losses are in practice the only losses which need be considered, and the iron losses divide, as explained elsewhere, into losses due to hysteresis (page 205, Vol. I.) and losses due to eddy currents (*loc. cit.*). Both losses expressed as lost power are proportional to the quantity of iron used,

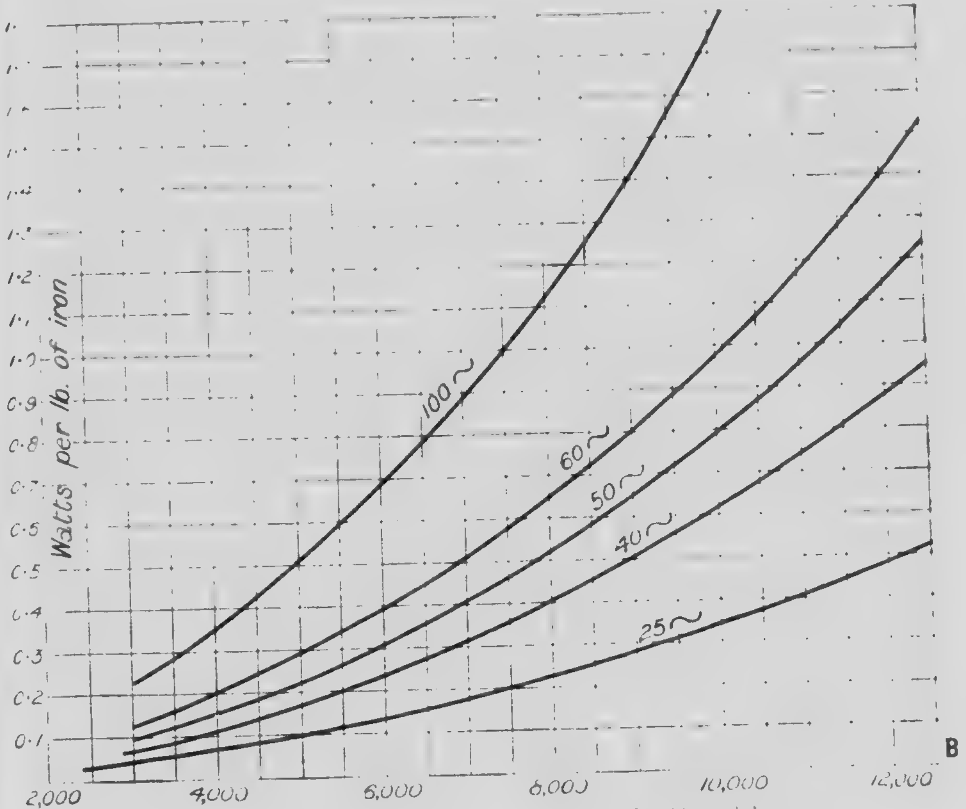

Fig. 900. Energy Losses of [illegible] Sheets for Different Flux Densities and [illegible]

whilst the first is also proportional to the periodicity and to $\mathbf{B}^{1.6}$. It may therefore be expressed by the equation

$$P_h = k_1 f \mathbf{B}^{1.6} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P_h stands for the hysteresis loss in watts per pound of the iron used, f stands for the frequency or periodicity, and $\mathbf{B}$, as usual, stands for the flux density. The power P_e lost in eddy currents is given in the equation

$$P_e = k_2 \mathbf{B}^2 f^2 \theta^2 . \quad . \quad . \quad . \quad . \quad (2)$$

where θ is the thickness of the iron and k_2 a constant. The materials available are the same as for the cores of dynamo armatures, namely good charcoal iron, and low-carbon steel, which has good permeability, a low hysteresis loss, and is cheap, but, owing to its somewhat high specific resistance, has a large eddy-current loss, especially at high periodicities. It is therefore only used, if at all, for transformers designed for low frequencies. There are also the magnetic low-carbon steel alloys manufactured by Messrs. I. Sankey and Son, which are referred to at pages 54

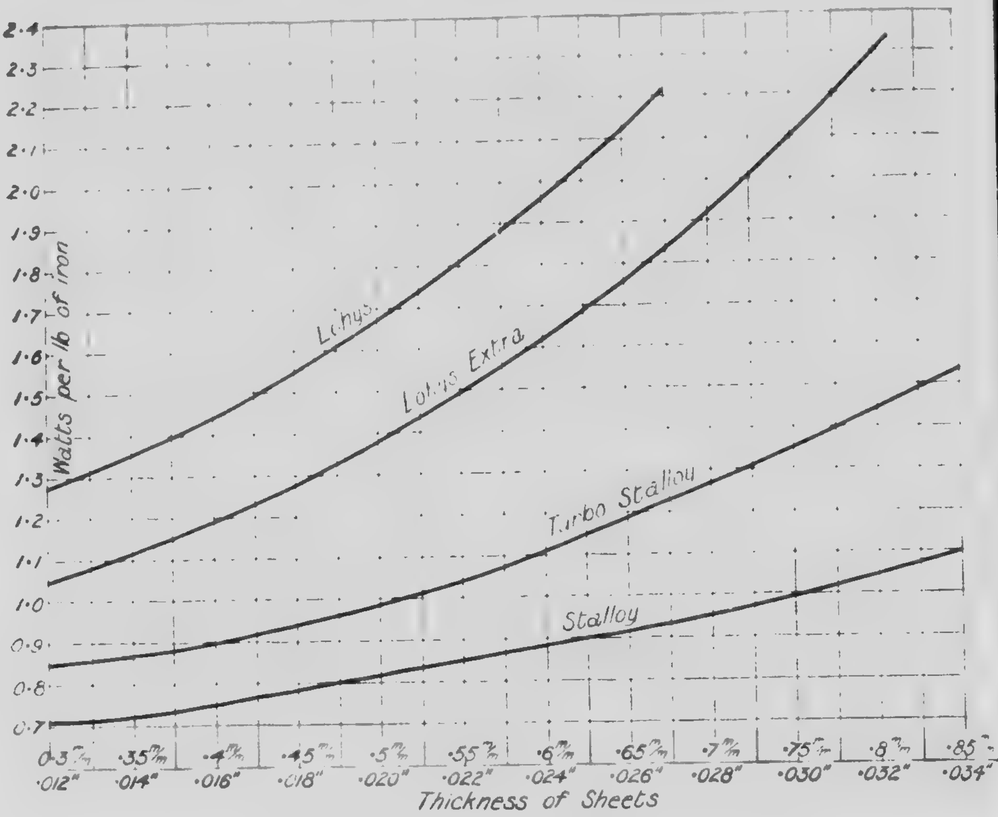

Fig. [illegible] Energy Losses at 50 ∿ for Sheets of Different Gauges.

and 55. These have good permeability and low hysteresis and eddy-current losses, but are somewhat expensive.

A word may be said here about the so-called magnetic "ageing" of iron and its alloys. It is some years since it was discovered that the iron losses of certain transformers which had been in service a few years had increased some 15 per cent. or more. Although the cause of this phenomenon has not been discovered, a remedy has been found in repeatedly annealing the material at a low temperature (say 100° C.) for a fairly long period. All kinds of good magnetic material can now be supplied and guaranteed to be free from this defect.

In transformer design, in addition to the magnetisation and permeability curves already given, it is convenient to have curves which give at a glance the iron losses per unit of weight of the material under different conditions. We therefore, in Fig. 900, reproduce curves for "Stalloy," one of Messrs. Sankey and Sons' most used alloys, in which the loss in watts per pound for sheets 18 mils thick is plotted against the flux density **B**. Each curve is for a particular frequency *f*, which is specified on it. Another useful curve is given in Fig. 901, in which the loss in watts per pound of four of the Sankey alloys is plotted against the thickness of the plate measured in mils and in millimetres. The losses are for a flux density of 10,000 lines and a frequency of 50 cycles. These curves are also from data supplied by Messrs. Sankey and Son.

Flux Densities. The flux densities adopted in practice depend mainly upon the periodicity and the method of cooling employed. Obviously a high flux density leads to economy in iron, and produces a lighter transformer, and from this point of view only the highest possible flux densities would be used. One has to remember, however, that high flux density means more than proportionate iron and eddy current losses (*see* Equations (1) and (2), p. 877), and that the heat which represents these losses has to be dissipated. Hence the more perfect the method of cooling, *cæteris paribus*, the higher may be the flux densities. Then again, the iron loss varies directly as the periodicity, and therefore at low periodicities less heat has to be dissipated for a given flux density, and the higher flux densities may be used if the cooling arrangements remain unchanged. These are the chief considerations; but, in addition, the value of the necessary magnetising current for high flux densities cannot be altogether neglected. The flux densities now usually employed are set forth in Table IX.

TABLE IX.—PRACTICAL FLUX DENSITIES FOR TRANSFORMERS IN KILOLINES PER SQUARE CENTIMETRE.*

Periodicity.	Open Type, A[illegible]	[illegible]	[illegible]	[illegible]
60	[illegible]	11 to 12	11·5 to 13	Same as for Water Cooled.
50	10 to 11	11·5 .. 12·5	12 .. 13	
40	[illegible] .. 12·5	13 .. 13·5	13 .. 14	
25	13·5 .. 14·2	13 .. 14·2	†13·5 .. 14·2	

These curves enable a rough start to be made with the design of a transformer for which the full-load output and efficiency are given. For instance, if the transformer is to have an output of 500 *kv.a.* and a full-load efficiency of 98·5 per cent. at unity power factor, the total loss will be of the order of 7,500 watts (500,000 × 0·015). If this be divided between the iron and the copper in the ratio of 2 to 3, a ratio which approximately obtains in modern practice, it will mean that 3,000 watts will be lost in the iron and 4,500 watts in the copper. The next point to decide will be the flux density, which will usually be lower in the yokes than in the core; but, taking for a first approximation, **B** = 10,000 and $\theta = 18$ mils, then we find from the curves that the loss per pound is 0·79 watt if stalloy be used, in which case the weight of iron will be 3,800 lb. (3,000 ÷ 0·79). For the other alloys for which particulars are given in the curves in Fig. 900, the weights would have to be less, owing to the greater loss per unit weight. How to dispose of the iron whose gross weight

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* For the figures in this table the Author is indebted to Mr. W. C. Kennett, B.Sc., A.M.I.E.E.

† Though the flux densities are the same, a poorer quality of iron may be used.

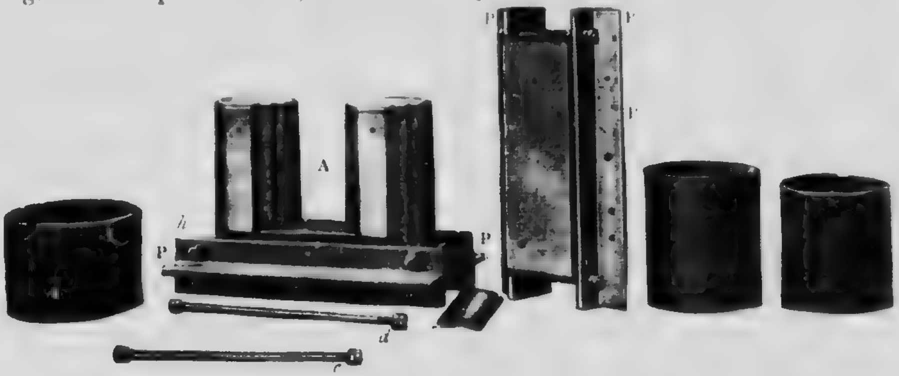


Fig. 902.—Magnetic and Electric Details of the Johnson and Phillips Standard Transformers

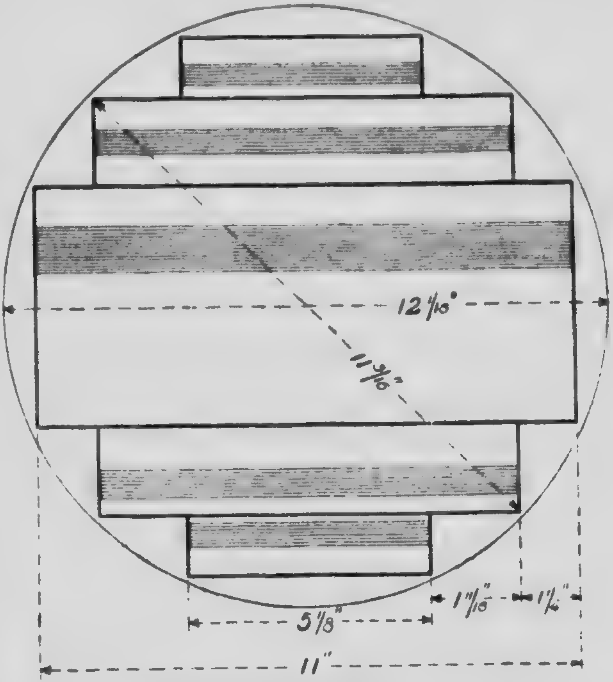
has thus been quite roughly ascertained is another problem, and opens up other questions in the design. If on working these out it is found possible to reduce the quantity of iron without raising the copper losses above 4,500 watts, the full-load efficiency will be higher than 98·5 per cent.

Magnetic Circuit Construction.—The general plans of the two chief methods upon which the magnetic circuits of many transformers have been designed for some years have been described on page 860, and the chief reasons for adopting either the "core" type or the "shell" type were there briefly explained.

In dealing with the actual details of either type, the designer has to keep continually in mind the cost of manufacture, not only as regards the quantity of material to be used, but also the labour to be expended in producing the finished transformer. The losses under no-load and load conditions are also of paramount importance.

The cost of producing and assembling the sheet stampings from which the core is built up has to be carefully thought out. In modern transformers these stampings are as nearly as possible rectangular in section, even when this leads to more joints in the circuit than were thought permissible when the transformers described in the historical section (pages 433 to 442, Vol. I.) were designed. Such a shape obviously conduces to economy of iron in producing the stampings from the rough sheet, and when, in addition, the number of sizes to be used is reduced to a minimum, further manufacturing economy is effected.

These general remarks and other points will be best understood from examples of actual circuits. Fig. 902 shows some of the details of construction adopted by Messrs. Johnson and Phillips for the single-phase core transformers illustrated in Fig. 885. In A the two cores are shown rising from the lower yoke, the laminations of which are tightly clamped between the stiff angle iron plates; the tightening-up bolts do not pass through the laminations. The upright cores are built up of rectangles of different width to secure what is known as a "stepped" core, to which further reference will be made presently. Each stamping is varnished on both sides, and the core, having been built up, is tightly compressed and baked at a regulated temperature for several days. The final thickness of the varnish varies from ½ to 1 mil (·0005 to ·001 inch), but even this very thin layer adds an appreciable percentage to the thickness of a plate of from 14 to 18 mils thickness, and represents wasted space so far as magnetic flux is concerned. In order that it may not penetrate so thin an insulating layer and cause wasteful eddy currents, the burr is carefully removed from the edges of the stampings.



F[illegible] Section of a "Stepped" Core for a [illegible] Transformer

The upper yoke is seen at B; when placed on the cores it forms a butt joint, to diminish the magnetic reluctance of which the contact surfaces are machined dead plane and the surfaces are pressed together by tightening up the nuts on the bolts *c* and *d*, which, one on either side, pass through holes *h* in the middle of the flanges of the clamping plates P P. The iron surfaces, however, are not allowed to come into actual contact, a sheet of manilla paper being interposed to prevent eddy currents circulating through the joint.

The "stepped" core referred to above is deliberately adopted to obtain the advantages (see page 23) of circular windings without sacrificing too much of the enclosed space. Incidentally, where space is lost in the corners in which there is no magnetic material a counter-balancing advantage of quite another kind is obtained, inasmuch as the ducts thus left through the core allow the circulation of cooling fluids, and thus enable the transformer to carry a heavier load, without excessive heating. A scale drawing of a cross-section of such a stepped core is given in Fig. 903, the dimensions being taken from a design for a transformer with an output of 1,000 *k*V.A. at 50 cycles.

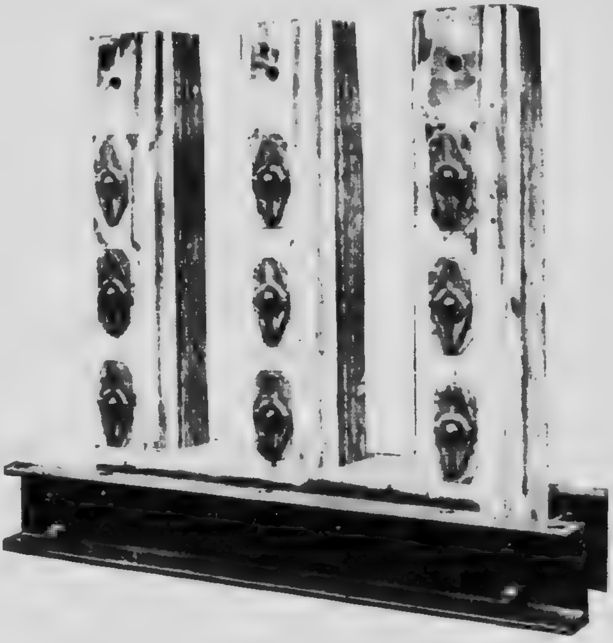


Fig. 904.—Ferranti Three-phase Core showing Yoke Clamps.

The stepped form of core is being more commonly used now than formerly, and a further example of it is given in Fig. 904, which represents the three upright cores and the bottom yoke of the Ferranti standard three-phase transformers, one of which will be found illustrated in Fig. 804. There is an important difference between the details of this magnetic circuit and that shown in Fig. 902. In Fig. 902 the magnetic joints at the end of the vertical cores are butt joints, whereas in Fig. 904 the stampings which form the top and bottom yokes are interleaved with the vertical stampings of the core from which each alternate stamping projects. It is claimed for this method that magnetic continuity is more approximately and more uniformly attained, leading to greater constancy of no-load losses, and that the working of the transformer is characterised by an absence of the humming noise which may often be observed, and which with butt joints may be due to the rapid attractions of the molar masses across the joints as the successive magnetic fluxes build up at the rate of double the periodicity per second. On the other hand, it is obviously much more costly to dismantle the transformer to replace a damaged coil should this unfortunately become necessary. The laminations are held together at the bottom and also at the top (Fig. 904) by lengths of rolled steel bolted together as shown, and additional stiffness is given by clamping plates and bolts through the vertical cores, which are not used in Fig. 902. The bolts are of course carefully insulated from the core iron.

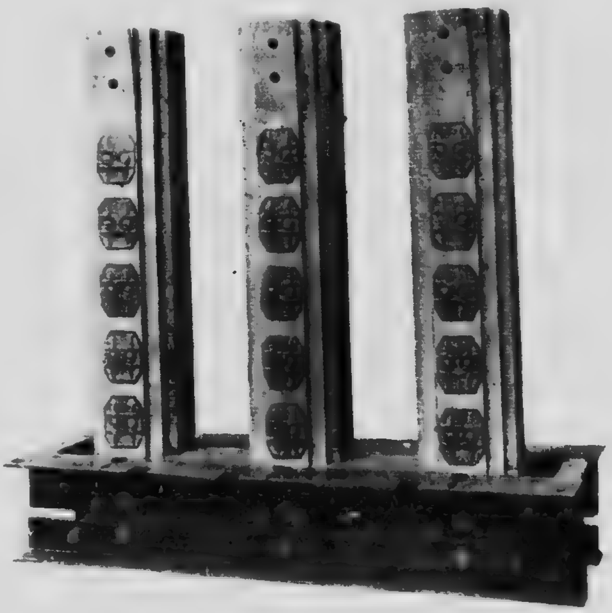


Fig. 905.—Brush Three-phase Core showing Yoke Clamps

The three cores and the bottom yoke of a 900-*k*V.A. 50-period transformer built by the Brush Electrical Engineering Company are shown in Fig. 905. The magnetic circuit of this transformer is built up of sheet steel 18 mils (0·018 in.) thick, the joints between the cores and the yokes at the two ends being imbricated or interleaved, as in the last example. The net cross-sectional area of the core, which is a stepped core, after allowing for the space occupied by the insulation between the laminations, is 475 sq. cms., whilst that of the yokes is 610 sq. cms., and the whole magnetic circuit weighs 4,500 lbs. The sheets of the upright cores are clamped between the gun-metal plates shown in the figure, and the bolts are insulated. The yokes are securely clamped, as shown, by bolts to a channel-iron frame. The horizontal bolts are insulated, and pass through the stampings, securely clamping the yoke to the core after assembly. Other particulars of this transformer and of its tank will be found at pages 872, 901 and 906 and elsewhere.

For small single-phase "core" transformers up to 50 *k*V.A. at 50 cycles, many manufacturers simply interleave the core plates at the corners of the circuit rectangle, as shown diagrammatically in Fig. 906, in which the plates of the next layer are, to show their positions, indicated by dotted lines as if they were slightly smaller than the front plates, which, of course, is not the case. In the particular circuit depicted, all the stampings are of the same size, namely that of the rectangle *a b d c*. Notwithstanding the use of well-machined butt joints by well-known firms experienced in transformer work, there is a big body of opinion to the effect that lapped joints have proved in practice superior to butt joints, however carefully constructed, and in the next type of transformer to be described such joints are used exclusively.

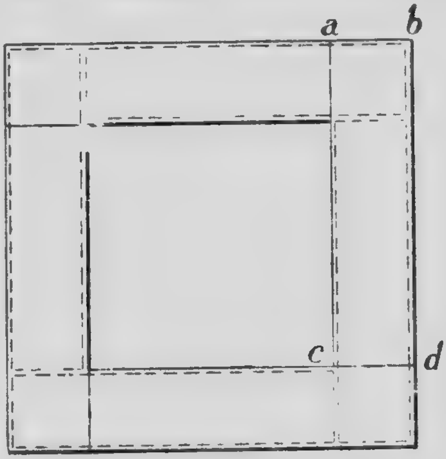


Fig. 906.—Interleaved Rectangular Core Plates.

The "shell" type of core construction has been illustrated in Figs. 887 and 898, and will be further referred to in connection with high-voltage transformers. In Fig. 898 the magnetic circuit is in horizontal and the electric circuits are in vertical planes, the core being built up of packets of stampings butt-jointed and held together by the angle irons and straining bolts shown in the illustration. One of the advantages not hitherto mentioned, which is claimed for this type of magnetic circuit is that the windings are readily accessible and are securely held in place by the encircling iron, so that the liability to buckle under the heavy mechanical strains developed on short circuit (*see* page 900) is reduced to a minimum. The arrangement of the electric circuits is described on page 801.

Quite recently the General Electric Company of Schenectady have re-designed their standard type (Type H) of transformer for outputs up to 100 *k*V.A., and it now has the form already illustrated in Fig. 860. This magnetic circuit may be regarded roughly as two magnetic circuits crossed at right angles, each similar to the "shell"-type circuit of Fig. 887, and when crossed having a common central core. If we imagine a thick shell transformer carcass like Fig. 887 split into two, each of one-half the number of laminations, and one of these swung round through 90° on the central vertical axis, it is obvious that with the same amount of iron the iron surfaces exposed for radiation would be practically doubled. Of course, the operation referred to cannot be performed, but a crossed circuit of the kind indicated can be built up as shown in Fig. 907, which is a plan of the iron circuit and windings of the General Electric Company's new Type H transformer. The ingenious way in which the four arms of the cross are keyed into one another to form the central core is particularly interesting.

The central core consists of four parts, each belonging to one arm of the cross. For each of these parts two different widths of stampings are necessary, and these are built up with the wider stampings in the middle to form the interlocking key. The outer vertical yokes are formed of stampings, all of the same width and length, assembled, as at the corners of Fig. 890, so as to form two lap joints top and bottom, the stampings for the horizontal parts of the cross being dimensioned to correspond.

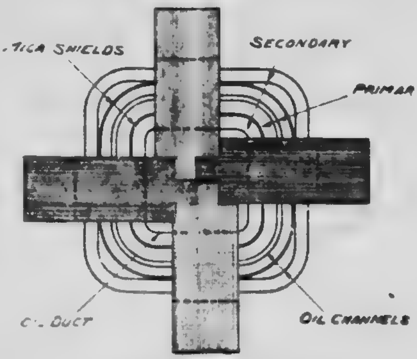


Fig. 907.—G.E. Standard Transformer, Plan of Core and Electric Circuits.

The coils being in the positions shown in Figs. 890 and 907, the transformer consists magnetically of four magnetic circuits in parallel, all the M.M.F.s being set up on the central core, and the closed circuit of any individual magnetic line consisting of a path similar to what would be set up in the circuit of Fig. 906. The quadruple circuit thus built up is of very low reactance, for, in such things as the selection of the material and in the smaller details of construction referred to elsewhere, no point is overlooked by the engineers of the Company. Details of the coils are given at page 892, and a further reference to the winding plan at page 1308.

A much more elaborate system of radial magnetic circuits magnetically in parallel has for many years been in use by the British Electric Transformer Company in the design and development of the Berry transformer, which has already been illustrated in Fig. 899. Three such transformers, without any mountings, are shown in perspective in Fig. 908, the base of the transformer being in each case turned towards the spectator. A plan of the transformer, somewhat similar to that of the General Electric Company's plan in Fig. 907, is given in Fig. 909. Instead of being magnetically the equivalent of two shell transformers crossed, it is equivalent to no fewer than twelve crossed shell transformers, making in all twenty-four magnetic circuits in parallel. In this way the radiating surfaces are very greatly increased, and the finished transformer (Fig. 899), except for its electrical fittings, resembles well-known types of radiators rather than a piece of electrical apparatus. In fact, it *is* a radiator with the radiating surfaces formed of the material in which a great part of the heat to be radiated is generated.

Referring to Fig. 900, it should be explained that the electric circuits are wound lower down in the space between the two dotted circles; outside these circles are the outer yokes seen in Figs. 899 and 908, and inside them is the iron of the central cores of the twenty-four magnetic circuits. It will be noticed that this core is built of four widths of stampings stepped as shown. The space at the shoulders of these steps is deliberately left clear so as to allow for the circulation of the cooling medium, whether air or oil, through the core. We deal, however, with the general question of cooling separately.

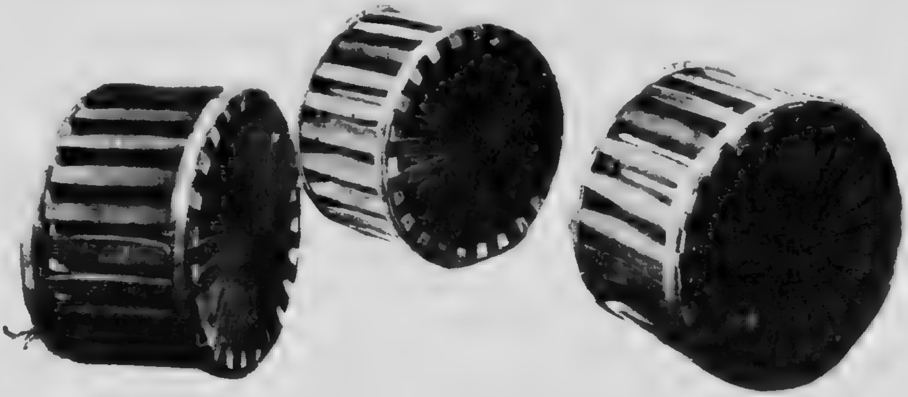


Fig. 908.—Elements of a Berry Three-phase Transformer.

V.—THE ELECTRIC CIRCUITS

The actual arrangement of the electric circuits in a transformer, apart from questions of insulation, is a comparatively simple matter, and the principles involved in the design of magnetising coils, which these circuits are, have already been explained in connection with the design of field magnet windings (*see* pages 23, 28 to 32 and 58). Some other points, more particularly the influence of the space factor, will be considered later, but attention may be called here to the fact that the main problem is, whilst obtaining the necessary number of turns, to keep the copper loss as low as possible, this loss being due to the C R heat generated in the coils.

Distribution of Windings.—As already explained, there are in a single-phase transformer two circuits, one usually consisting of many more turns than the other. For reasons given on page 862, we shall refer to the first as the high-voltage circuit, and to the second as the low-voltage circuit. If the space available for the windings has, in the development of the design, been already fixed by other considerations, it can be shown that, neglecting the disturbing influence of the "space factor," the heat loss will be a minimum if this space be equally divided between the two windings. This will provide us with a sufficiently close working rule for this section.

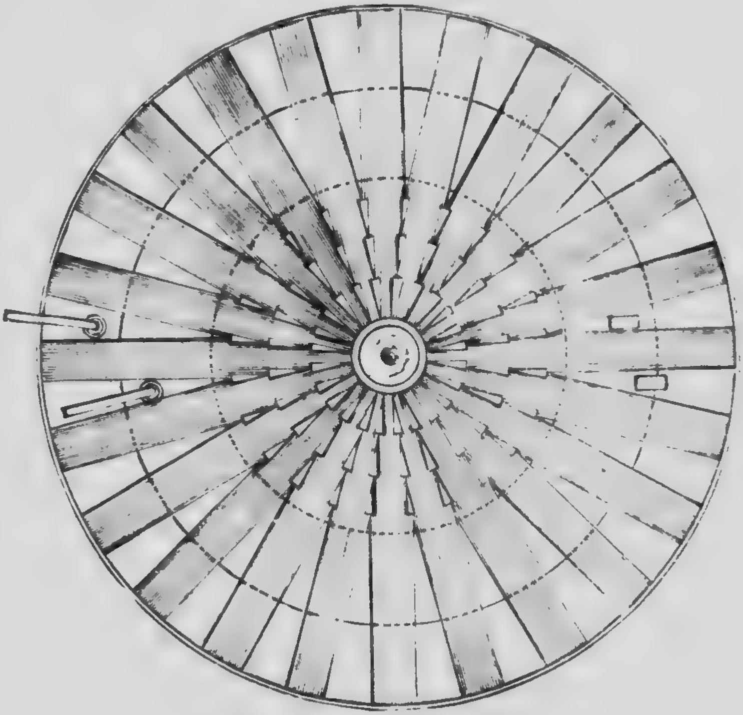


Fig. 909.—Horizontal Cross-section of Berry Transformer.

Insulating Materials.—The special conditions which the insulating materials used in transformers have to encounter necessitate a word or two in addition to what has been said about insulators in other parts of this book. Efficient and economical insulation is one of the prime essentials of good transformer design, and the choice of materials which will not deteriorate under the conditions of working is also of prime importance. The material referred to is that which is to insulate the coils from the iron and from one another, and the new condition, which does not apply to most cases of electrical insulation, is that the material in most modern transformers is brought into contact with hot oil.

Of the available materials, *mica*, which is such an invaluable, though somewhat expensive, insulator for many electrical purposes, is only used by some designers in air-cooled transformers, as they are of opinion that it deteriorates when in contact with hot oil. Again, *presspahn*, which is also widely used for other purposes, becomes pulpy under hot oil. *Vulcanised fibre* has also to be rejected, as the sulphur it contains is acted on by the hot oil.

It would be wearisome to go through the long list of composite insulators which have been placed on the market, and we shall therefore be content to mention two which are not acted upon by hot oil. One of these is *varnished cloth*, which is widely used in small transformers, and the other is known as "*Bakelite*," which is also mechanically strong, and can be used for cylinders upon which the low-voltage coils are wound directly.

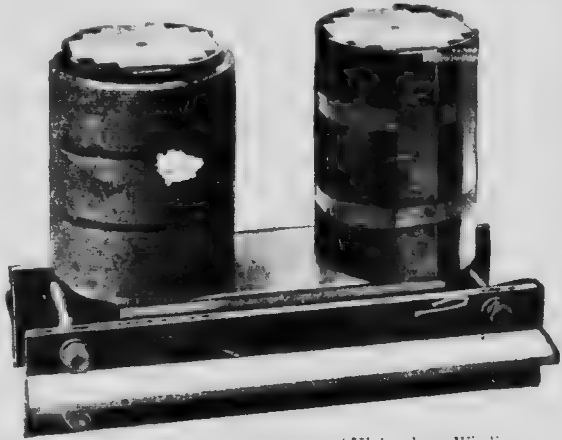


Fig. 910.—Insulation and Arrangement of High-voltage Windings on Core.

The insulating oil which is used in transformers for cooling purposes will be referred to later (*see* page 924).

It has been already explained (*see* pages 862 and 863) that there are two general methods of arranging the windings, known respectively as the "sandwich" (Figs. 878 and 880) and the "concentric" (*see* Fig. 879), and the general advantages and disadvantages of the two methods have been briefly explained. We can therefore pass at once to descriptions of actual windings.

Concentric Windings.—This method of winding is usually adopted for small and medium-sized transformers of the core type. In many cases, but not always, the coils are circular, a shape which encloses the maximum area for a given periphery (*see* page 23), and which has the additional advantage that with large over-load currents or sudden very arge currents, caused by a short circuit, the mechanical forces do not tend to buckle the coils. With straight-sided coils the forces tend to bow out the straight part and make it assume a circular shape, a movement which tends to chafe the insulation and to lead to a breakdown. Other advantages are detailed on page 863

Johnson and Phillips Transformer.—In the figure (Fig. 902) showing the magnetic circuit of the Johnson and Phillips single-phase transformer there are shown at the side some of the wound coils ready to be slipped on the cores. The concentric coils are circular and former-wound. Each layer is carefully insulated from adjoining layers by special insulating material unaffected by oil. The coils are then thoroughly dried and insulated in a vacuum plant, and each of the high-voltage coils is taped up with oiled linen or varnished tape. Before placing the coils on the core the latter is insulated, as shown on the right-hand limb in Fig. 910, and the high-voltage coils are slipped on as shown on the left-hand limb. The high-voltage winding is divided into several coils to reduce the voltage per coil. The continuance of this stage of the assembling is shown in Fig. 911, in which it will be seen on the right-hand limb that an insulating cylinder has been slipped over the high-voltage coils before the low-voltage coils are placed over them.

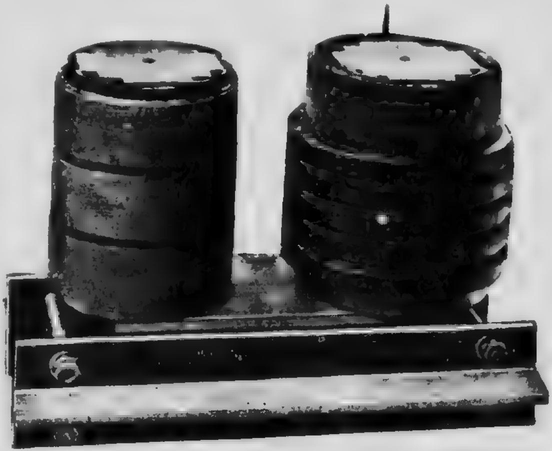


Fig. 911.—Insulation and Arrangement of Low-voltage Windings on Core.

The Ferranti Transformer.—The high- and low-voltage coils used for a Ferranti transformer appear in Fig. 912, which shows a single-phase transformer in the "assembling" stage of construction. The low-voltage coil L, with proper insulation interposed, is placed next the stepped core as shown at L′, and some details of its construction are given below. It is held in position by wooden packing strips, which, with the stepped core, leave ventilating ducts for the circulation of the oil. It may be noted that the leads *l l* coming from this coil are very effectively stranded.

Where voltages of over 3,300 volts are used a compressed impregnated paper shield is slipped over the low-voltage windings. The shield is treated with an impregnating compound to protect it from the action of the oil. If required—but this firm does not recommend its use—a metallic earth shield is placed next to the low-voltage coils and inside the impregnated paper tube; it is efficiently connected to the transformer frame, which is provided with an earthing lug, so that it, in its turn, may be connected to a good "earth."

The high-voltage coils, which, as described presently, are wound in sections, are slipped over the impregnated paper cylinder as shown, and are connected together and to the terminals as may be partly seen in Fig. 894, and more fully in Fig. 912, in which is given a part section through one of the limbs.

By the courtesy of Messrs. Ferranti we are able to show in Figs. 913 to 915 some interesting details of the processes of manufacture of these low- and high-voltage coils. Fig. 913 is from a photograph showing the actual winding of a low-voltage coil. The conductor, which consists of copper strips, apparently in this case six in number, is drawn forward by the rotation of the wooden mandril M M, to which its end is clamped. The strips are electrically in parallel, but are lightly insulated from one another by thin paper, which is interleaved with them as they approach the guide block *b*. After passing this block they are well taped transversely, the stranded conductor passes on to the mandril, and the coil (L, Fig. 912) is built up, the tension of the winding being regulated by the guide block *b*, which is adjustable.

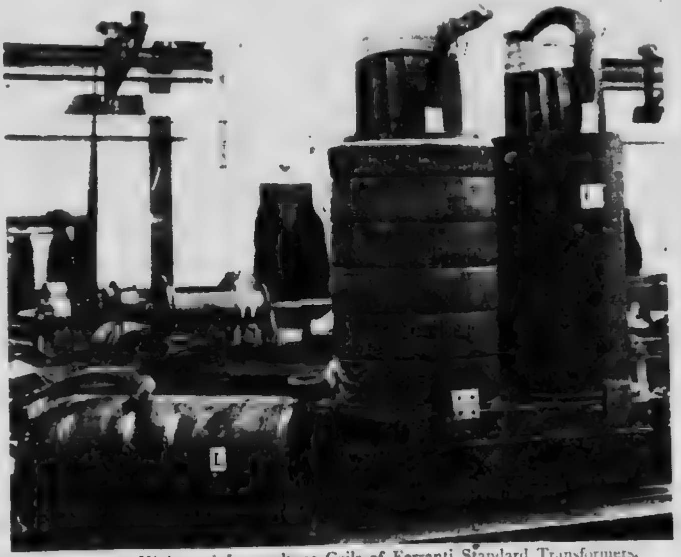


Fig. 912.—High- and Low-voltage Coils of Ferranti Standard Transformers.

The high-voltage coils are more difficult to construct. For reasons given elsewhere, the end coils next to the supply line are more carefully wound and insulated than the others, and therefore we show in Fig. 914 one end coil completed and its next coil with the first layer of fine wire already on the wooden mandril. It will be noticed that the wire already insulated is being still further protected by additional insulating material fed on in the process of winding; also that the coil is built up in narrow sections, there being but a few turns in each layer, and that successive layers are very carefully insulated from one another by strips of insulation which project well beyond the outside turns.

The next process is to tape the coils so wound after they are removed from the mandril and temporarily bound. The tape is served on with the requisite tension, the tape bobbin, of course, passing through the coil to be taped. Coils in various stages of taping are shown in Fig. 915. Coils *a a* have merely had a hand-serving of tape to hold them together when removed from the winding mandril, coils *b b* appear with one or more layers of tape, and a still further stage is shown in coils *c c*, which consist of two or more coils like *b b* placed on top of one another, and the whole again taped heavily. Piles of completed and impregnated coils are shown at C C, a low-voltage coil at L, and one of the inner shields at S.

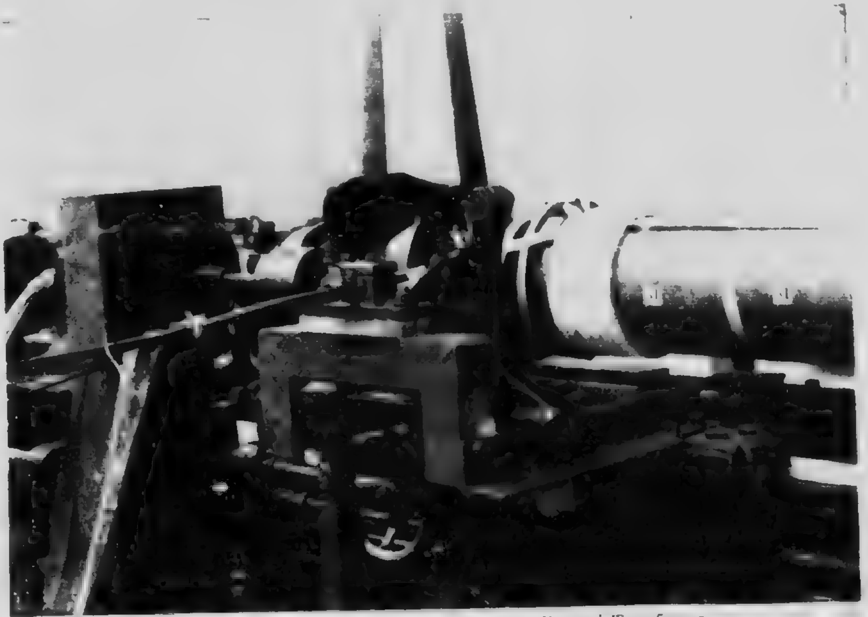


Fig. 913.—Winding of a Low-voltage Coil for a Ferranti Transformer.

The Brush Transformer.—In this transformer (Fig. 805), manufactured by the Brush Electrical Engineering Co., the windings are also circular in shape and concentric, and as in the last example the low-voltage winding is placed next to the core, one phase being on each limb of the three-phase transformer, from which it is separated by an insulating tube. For round wire, or for strip, of which the greater dimension does not exceed $\frac{1}{8}$ in., double-cotton covering is used, but for larger strip strong linen tape is served on during the winding, and the different layers of strips in parallel are separated from each other by manilla paper. If the coil consists of more than one layer the layers are insulated from one another by layers of varnished cloth. The coil is impregnated after winding, then taped with insulating material and again impregnated. Proper ventilating ducts for the circulation of oil are provided between the core and the low-voltage winding.

The high-voltage winding is divided, as shown (Fig. 895), into a number of coils to facilitate replacement and to reduce the voltage between the layers. An insulating cylinder is interposed between the low-voltage and the high-voltage coils, and when an earth shield is required it is placed inside this cylinder. The high-voltage conductor is double-cotton covered, and for not fewer than fifteen turns from the terminal ends of the winding it is specially insulated to withstand full-line pressure between individual turns so as to prevent breakdown due to pressure rises or surges on the system. Varnished cloth is interposed between layers, and several times during winding each separate coil is impregnated with varnish *in vacuo* and under pressure, and then thoroughly baked. The result claimed is a waterproof and durable coil impervious to oil.

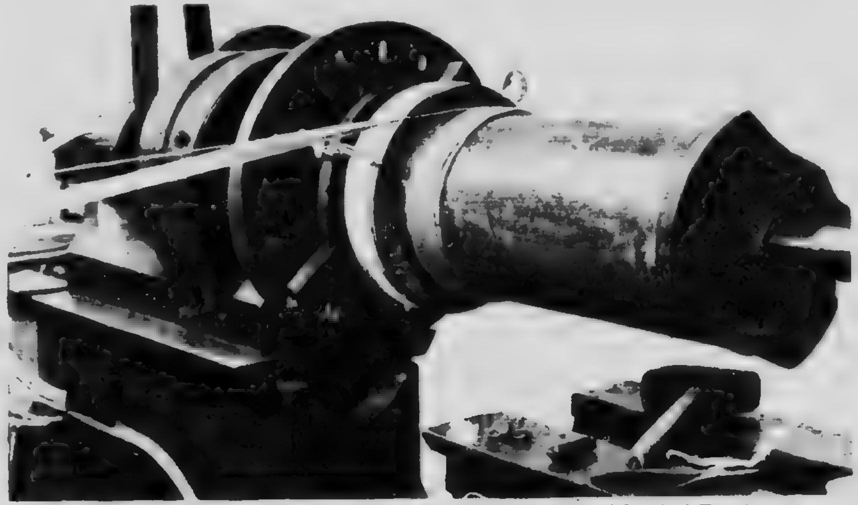


Fig. 914.—Winding a Reinforced-end High-voltage Coil for a Ferranti Standard Transformer.

General Electric Transformer.—The arrangements of the coil in the General Electric Company's Type H transformer is clearly shown in the plan already given (Fig. 907). The winding is concentric though the coils are not quite circular, being rather, in plan, square-shaped coils with rounded corners. A low-voltage coil is placed next to the core; outside this are two high-voltage coils with an air space or oil channel between them; and finally, outside all, is the remainder of the low-voltage winding in the form of a coil somewhat differently shaped in plan so as to leave fairly wide oil ducts between the high- and low-voltage windings at the four corners. The shape of the core is also such as to leave four oil ducts inside the innermost winding.

The insulation between high- and low-voltage windings consists of thick mica shields built up of layers of mica, the rounded corners of the coils not requiring the mica to be bent too sharply, and so risking the danger of its cracking. The mica cylinders project well beyond each end of

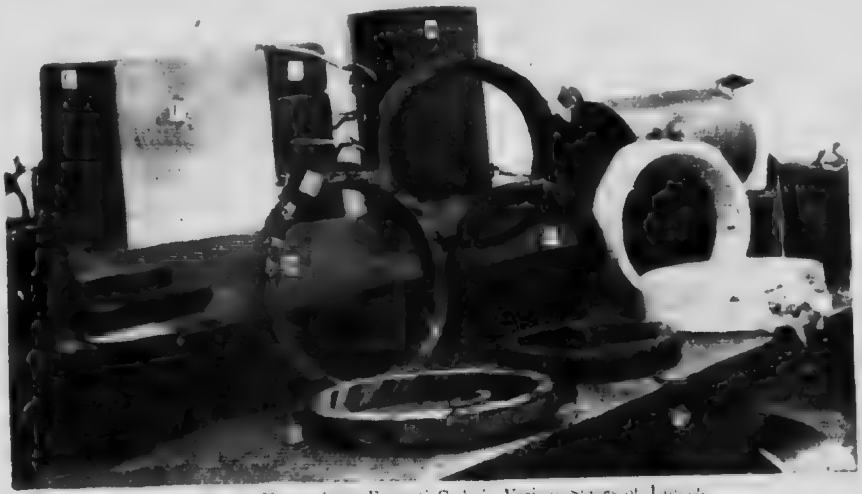


Fig. 915.—High-voltage Ferranti Coils in Various Stages of Taping.

the windings, and are sufficiently thick to stand a voltage of 40 to 50 kilovolts. The circuits may therefore be regarded as safe for voltages up to 2,500. The successive layers of the windings of each coil are separated by insulating fibre, which also projects beyond the ends of the coil so as to separate effectively the end turns of successive layers which are the turns at the greatest P.D.

In this section, and in other parts of the book, mention has been made from time to time of the vacuum drying and impregnating tanks used in finishing the coils after winding. By the courtesy of the General Electric Company we show in Fig. 916 one of the stages of the process. The "vacuum plant" referred to on page 889 consists essentially of a tank or drum which can be made airtight and be heated. It may be, but is not necessarily, similar to the tank in Fig. 916. When the coils have been made ready, as described on page 893, they are introduced into the tank, which is closed up, connected to an exhaust pump and heated. The reduction of the air pressure causes the moisture to evaporate completely at a much lower temperature than 100° C., and thus the insulation, whilst being effectively dried, is not in danger of being injured by overheating. The coils are kept some hours in the vacuum tank, the temperature and the partial vacuum being maintained throughout. They are then transferred to another tank, and completely immersed in a hot molten insulating compound. The tank lid is closed and clamped tightly and pressure applied to the contained air. This thoroughly impregnates the whole of the insulating material surrounding the conductors, and when the process has continued long enough, as shown by experience, the tank is opened and the coils removed. The compound used by the General Electric Company has a high melting-point, so that it may be unaffected by the highest normal temperature of the tank under full-load currents; it is also non-hygroscopic, and is permanently unaffected by the insulating oil of the transformer tank.

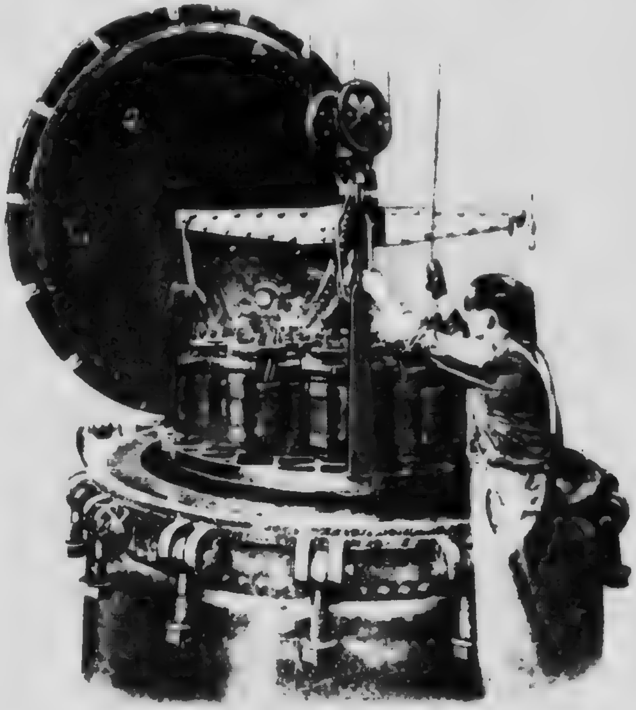


Fig. 916.—G.E. Transformers being removed from Impregnating Tank.

Berry Transformer.—The situation of the coils and the space occupied by them in the Berry transformer are shown in Figs. 917 and 918. Fig. 917 is a horizontal cross-section, and gives also some details of the multiplex magnetic core and the twenty-four return yokes. Fig. 918 is a vertical section, giving further details of the distribution of the windings. Half the low-voltage winding is placed next to the iron core and inside the high-voltage winding, whilst the remainder is placed next to the iron of the yoke pieces. The high-voltage coils are former-wound in sections as shown, and, when assembled on the core, ample air or oil ducts, secured by distance pieces, are left between the different sections. The coils are also so connected that the potential difference between any two of them is only a small fraction of the total potential difference, the points between which the largest potential difference occurs in the windings being separated by the full length of the core. To attain this end a heavily-insulated lead F (Fig. 918) is brought up from the bottom of the transformer between two sections of the yoke. Between the high-voltage coils and the low-voltage windings which they encircle there is first of all, and next to the low-voltage coils, a finely woven earth screen of copper gauze, which is surrounded by a built-up cylinder of sheets of bonded mica wrapped round whilst hot.

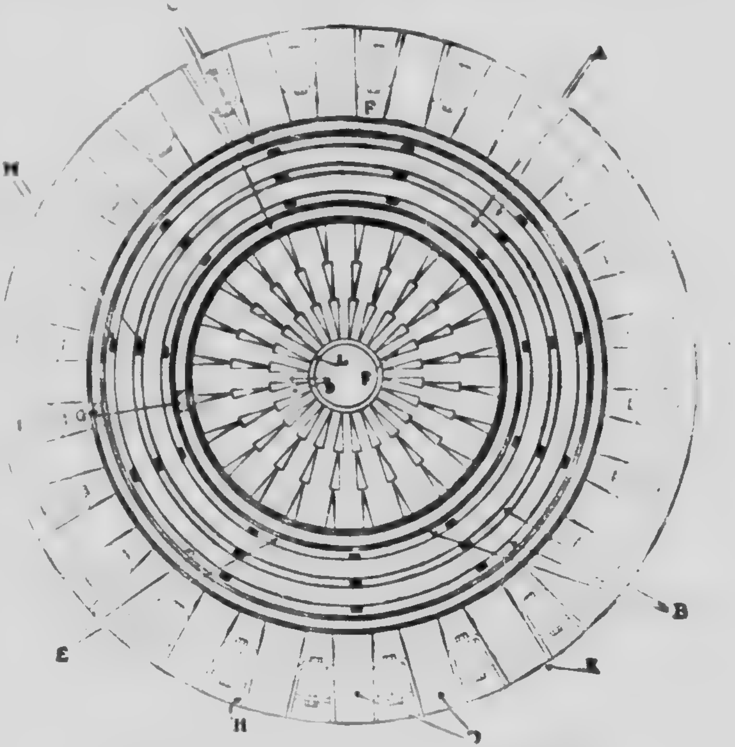


Fig. 917.—Cross-section of Berry Transformer, Core and Windings.

The low-voltage windings are wound, the innermost directly on the insulated central core, and the outermost over the high-voltage coils when the latter have been placed in position and have had a solid insulating cylinder of mica built over them similar to the one built over the inner windings. Another earth shield or some other earthing device is interposed at this stage.

A single-phase 500 *kv.a.* transformer of this type was illustrated in Fig. 889. Exclusive of mechanical details, such as end plates, bolts and wheels, it is 42 inches in diameter, and stands 45 inches high. The voltages are 6,000 and 440 volts in the two windings, giving a voltage ratio of 13·6 to 1.

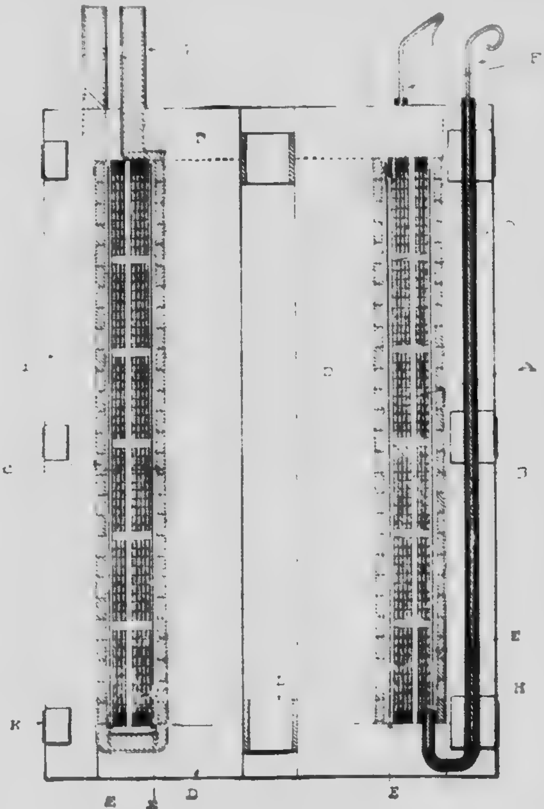


Fig. 918.—Vertical Section of Berry Transformer, Windings and Magnetic Circuit.

The actual process of winding on the low-voltage windings may be of interest to our readers. It is shown in Fig. 919, which is from a photograph taken in the workshop. The unfinished transformer is supported on a removable mandril between two headstocks, one only of which is shown. The heavy conductor, it will be noticed, is made up of layers of copper strip, which are bound round with insulating tape as they are wound on. The photograph also shows other details of the construction which have been referred to in previous paragraphs.

Sandwich Windings.—The "sandwich" method of arranging the windings has been diagrammatically illustrated in Figs. 878, 880 and 881. It is most frequently used in transformers of large output of the shell type, and also for high-voltage working. A Siemens transformer of this type has been illustrated in Fig. 898, in which the thin sandwiched coils, consisting alternately of high- and low-voltage sections, are arranged in vertical planes. The sections are separated from each other and from the core by strips of hard wood and sheets of presspahn. The latter, projecting between the coils, can be plainly distinguished in the illustration. One of the advantages of the vertical arrangement of the coils is that it allows spaces to be left between the sections and the presspahn and wooden straps through which the cooling and insulating oil can circulate freely. The wood and presspahn are insulating materials, but the oil is relied on to provide the principal insulation.

The working advantage of the sandwich method is the reduction of the magnetic leakage between the two circuits to a minimum, thus diminishing

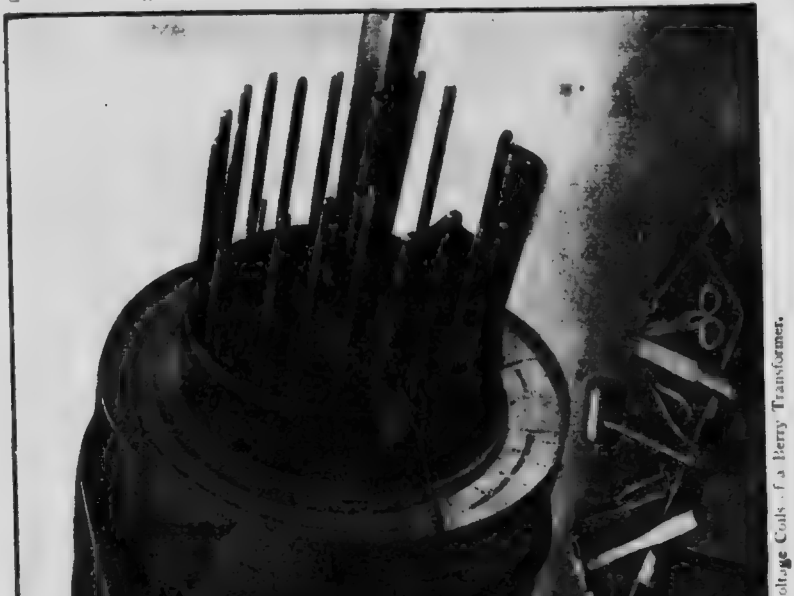


Fig. 919.—Winding the Low-voltage Coils of a Berry Transformer.

the inductive drop. On the low-voltage side it allows of coils consisting of one turn per layer. The coil used may be described as being of a slab form, as shown in Figs. 920 and 921, which are views respectively of an unfinished and of a finished coil, as made by the General Electric Company of Schenectady. The coils are former wound, copper strips being used for the low-voltage windings, and after winding are thoroughly baked and treated with insulating compounds in the usual way already described. They are then carefully taped and subjected to a final series of treatments and bakings. The insulation of the coils nearest the terminals is heavily reinforced as a safeguard against the excessive voltages of surges referred to elsewhere. The assembled coils of a 66,000-volt 500-*k*v.a. transformer made by the same firm are shown in Fig. 922. It will be noticed that the high- and low-voltage coils are in groups, and not arranged alternately as in the Siemens transformers.

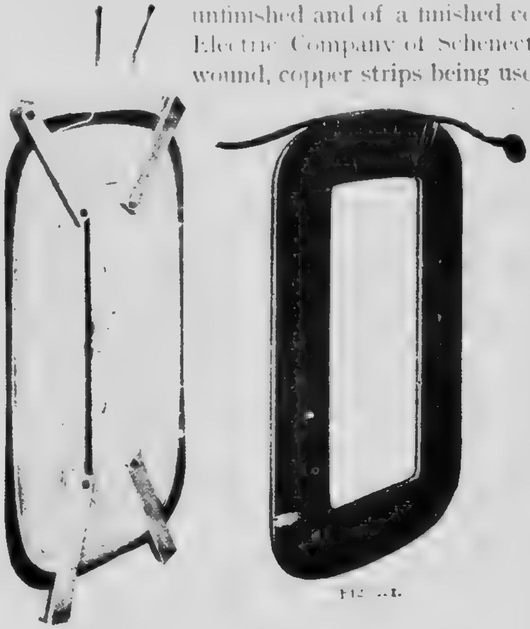


Fig. 920.

Fig. 921.

The Winding of "Sandwich" Coils.

We cannot better conclude this section than by depicting in Fig. 923 the interior of the winding section of a transformer works. This picture is taken from the *Electrical Review*, and has been reproduced from a photograph taken at the works of the British Electric Transformer Company, Limited, at Hayes, Middlesex. The reader may be interested to compare it with the similar picture of the armature winding shop at Messrs. Mather and Platts' works given in Fig. 80.

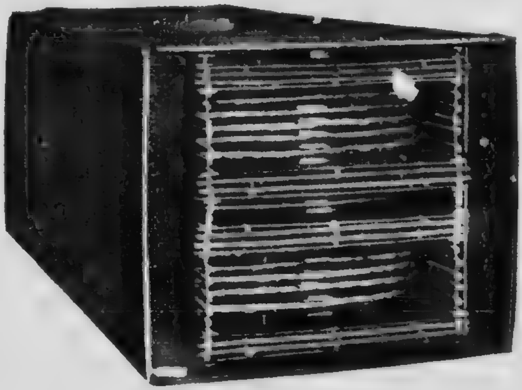
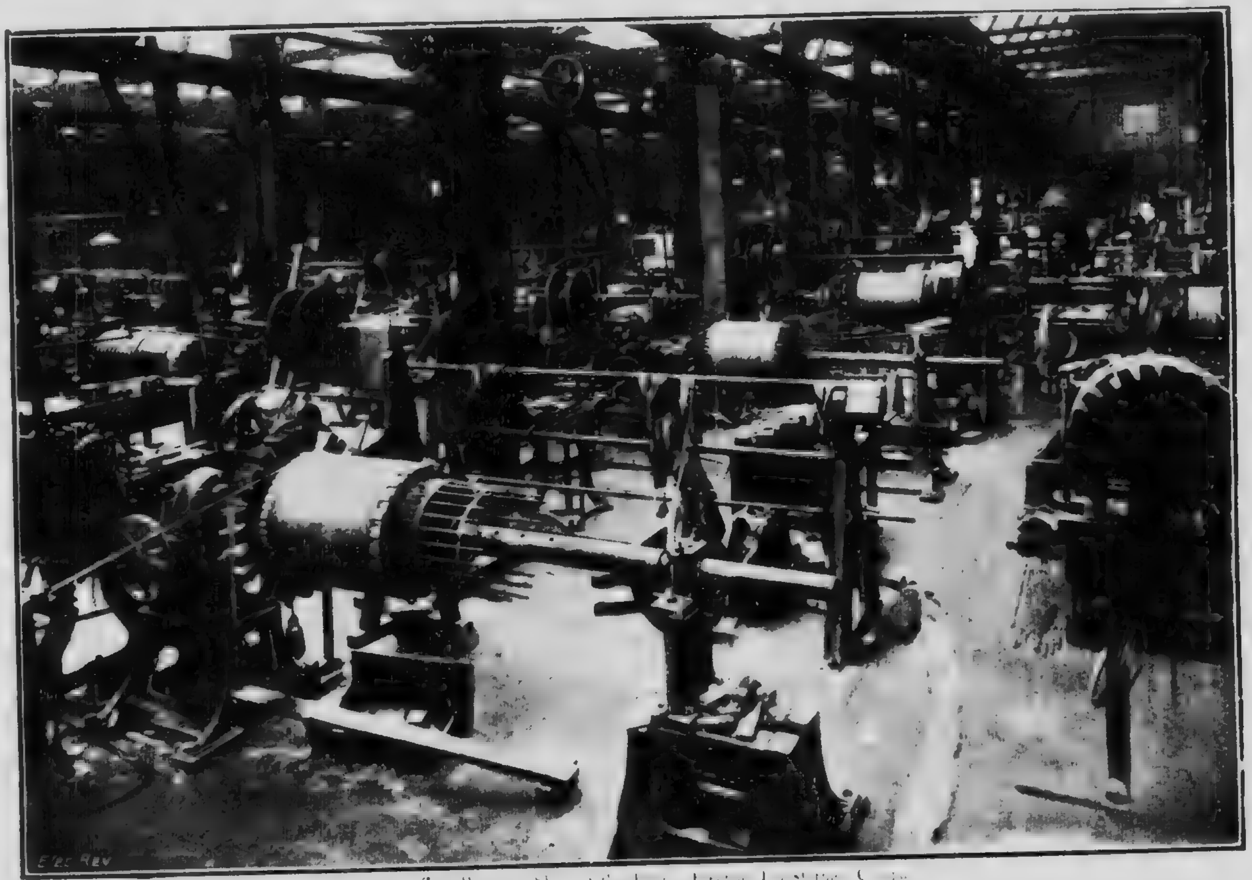


Fig. 922.—Assembled "Sandwich" Coils of a 66,000-volt 500-kv.A. General Electric Transformer.



[illegible] The W[illegible] Sh[illegible] [illegible] L[illegible] Electric [illegible] C[illegible]

VI.—OTHER DETAILS OF CONSTRUCTION

Connections to Terminals.—The connections of the electric circuits of a transformer to its terminals by which it is to be brought into service are quite simple, though some care is necessary to secure the necessary insulation where high voltages are employed, and to guard against surges especially in the case of tappings on the high-voltage side. We are concerned here with matters influencing the constructional details of such connections. The general subject of the connections of the circuits, apart from such constructional details and the necessities arising therefrom, are dealt with elsewhere (*see* pages 940 to 953).

In *single-phase* transformers without any tappings there are simply two terminals on the high-voltage side, and two on the low-voltage side. For ordinary voltages and services ebonite is used as the insulating material, whilst for higher voltages porcelain is employed, and for the highest voltages the terminals are very specially designed. Many forms of terminal insulators have been shown in the preceding illustrations, which should be again referred to in this connection. The special terminals for the highest voltages will be referred to later.

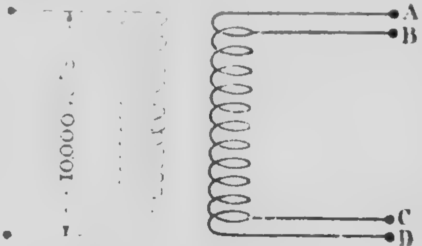


Fig. 924.—Circuits of a Single-phase Transformer with Low-voltage Tappings.

Where the transformer has its high-voltage side connected to a public supply service and the consumer desires to be able to adjust the voltage available, tappings to extra terminals are supplied on the low-voltage side at a small additional cost. In the case mentioned on page 867, the Johnson and Phillips transformer have four low-voltage terminals, the circuits being as shown diagrammatically in Fig. 924. The transformer referred to was to be used nominally for stepping down from 10,000 volts on an overhead line to 3,300 volts for mining work. The two taps are placed one at either end of the low-voltage windings, and the normal voltage of 3,300 volts can be obtained by using either A and C or B and D. If a higher voltage is required, A and D will give 3,450 volts, whilst B and C will give the lower voltage of 3,150 volts. The variation is therefore about + or − 5 per cent. on the normal voltage.

Examples of connections for tappings on the low-voltage side, with reference to the requirements of rotary converter starting, are given later. Beyond taking proper care of the insulation, tappings for these and other purposes present no difficulty, and need not detain us further here. They will be more conveniently dealt with when the special purposes for which they are required are under consideration.

Tappings on the high-voltage side have to be more carefully designed, both because the voltage is higher and also because of the greater danger of destructive heavy surges occurring on this side through short circuits and other accidents on either side.

Where such high-voltage tappings are required the usual British practice is to bring them to a terminal board, which is made part of the transformer, instead of bringing the leads to an outside switchboard and using specially designed switches. This terminal board and all that it carries is immersed in the insulating transformer oil, and the actual connection required is made by a link or links, to move which the transformer must be switched out of circuit, the case opened up, and the oil cleared out of the way. This may seem a cumbrous method of procedure, but as a matter of fact in actual practice a change in the tapping is seldom required and can be made deliberately. If and when rapid and frequent changes are contemplated, the more costly equipment alluded to above must be provided.

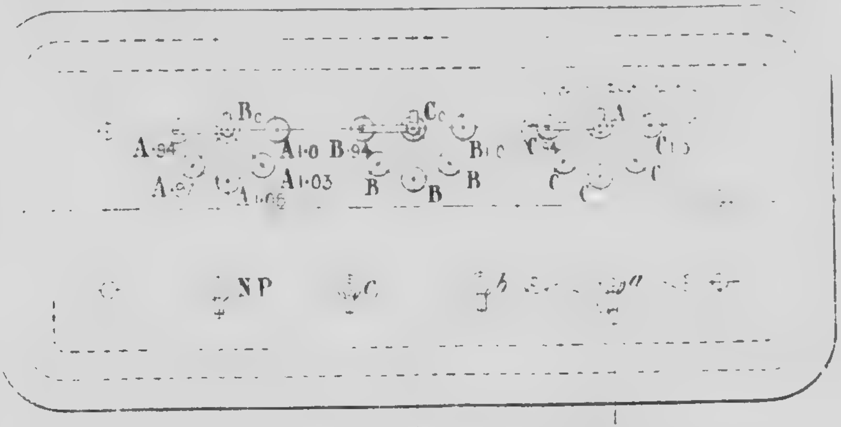


Fig. 925.—Brush Three-phase Transformer Terminal Board.

The plan of the terminal board of a Brush three-phase transformer described elsewhere (pages 873 and 885) is shown in Fig. 925; reference should also be made to Fig. 805, where this board will be seen in position. The maximum voltage on the high-voltage side is 12,000, and there are six leads from the coils of each phase, the phases being "mesh" connected. Five of the leads are tappings at one end of the winding, and the sixth, which is from the other end, is connected to the external terminal. The arrangement will be better understood by reference to Fig. 926, which is a diagram of the internal connections. In both figures the phases are marked A, B, and C on the high-voltage side and *a*, *b*, and *c* on the low-voltage; thus the winding $a_6 a_1$ is the secondary of the primary winding

$A_0 A_1$, but to avoid awkward crossings of lines in the diagrams these windings are not shown opposite one another in Fig. 926. It should be noted that the movable links are used to make the mesh junction of one phase to the next, the B terminal, for instance, being the pivot of the link to the A tappings.

The tappings are electrically connected to provide for variations of voltage in steps of 330 volts, which is 3 per cent. on 11,000 volts. The lowest voltages intended for the different tappings are therefore 10,340, 10,670, 11,000, 11,330, and 11,660 volts, rising in each case by 330 volts to the next tap or in the last case to 12,000 volts, the maximum high-voltage. For each of these the pressure on the low-voltage side is to be 2,750 volts, but it of course fluctuates with any change in the high-voltage side. The actual coils from which the tapping leads run are the three top coils of each range seen in Fig. 895.

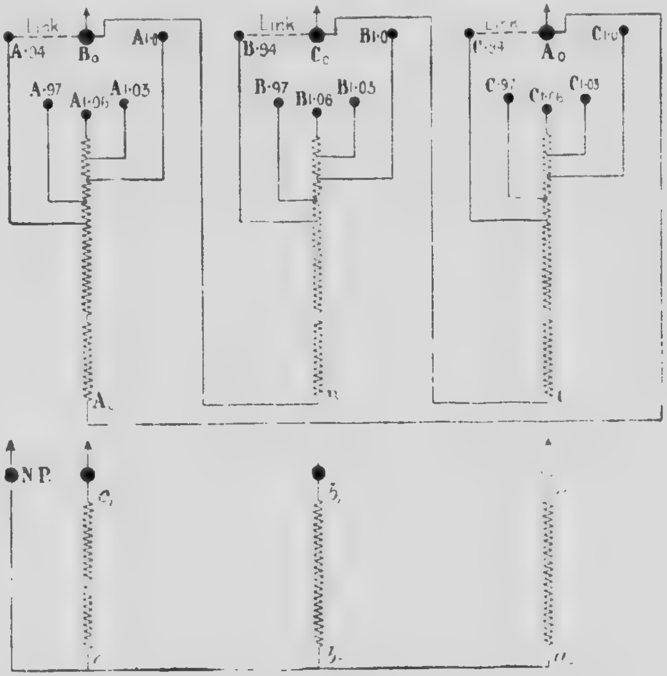
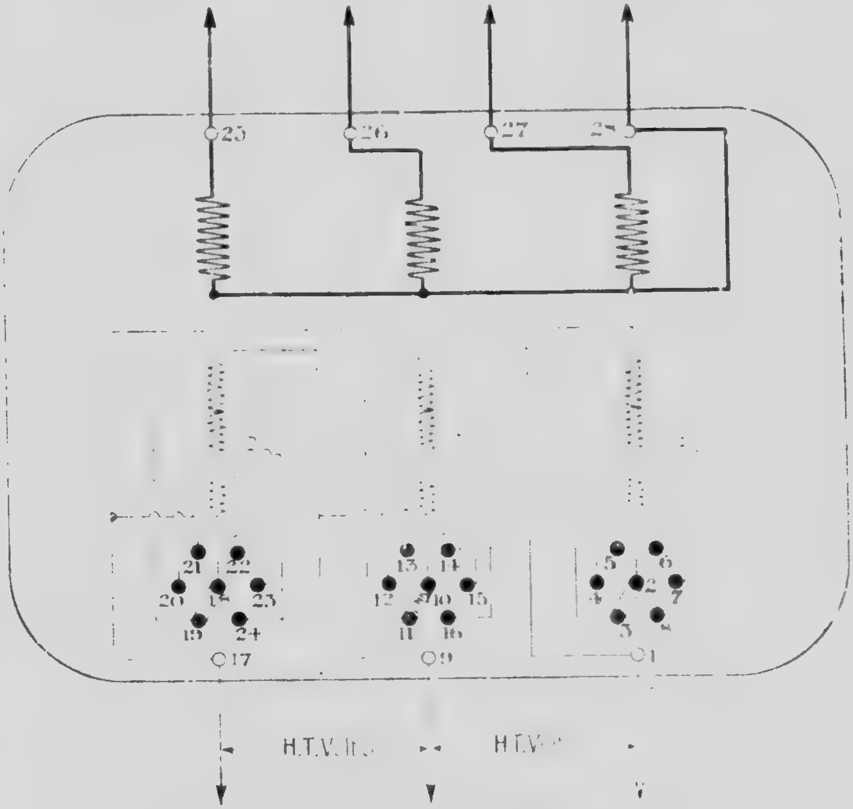


Fig. 926.—Circuits and H.-V. Tappings of a Brush Transformer.

The ends of the leads from the various coils are brought to porcelain insulators, the shape of which is partly shown in Fig. 895. Where these are intended to make connections to external circuits they are provided with suitable thimbles and sockets into which the external cables can be sweated. These cables are brought into the tank through insulat-ng bushes fixed in the top casting of the tank illustrated in Fig. 943. The leads between the windings and the terminals on the high-voltage ide run in insulating tubes which, owing to the long distance between ils and terminals, pass through porcelain bushes in a stout intermediate lamping rod R_1 R_1 seen in Fig. 895. These tubes, which are impervious to hot oil, are designed to hold the leads securely in their places in the



[illegible]

event of accident or of a short circuit, which would produce heavy currents giving rise to large mechanical forces on the leads.

The low-voltage leads, which are in much stouter tubes, are very clearly shown with the details of their mountings in Fig. 895. The phase leads *a*, *b*, and *c* rise directly from the upper ends of the windings, the lower ends of which are to the neutral bar, which is mounted horizontally on the clamping channel iron of the lower yoke. From this bar the lead is taken vertically to the "N.P." (Fig. 925) terminal.

An excellent example of the care with which such tappings are arranged is given in the *three-phase* Ferranti transformer already described (*see* pages 871 and 872). Attention was called on page 871 to the numerous high-voltage tappings shown in Fig. 894, and to the special terminals to which these tappings are led. The scheme of the connections is shown diagrammatically in Fig. 927, from which it will be gathered that the general plan is that the high-voltage side is "mesh" connected and the low-voltage side "star" connected with a fourth terminal connected to the neutral point of the star. The main high-voltage terminals are numbered 1, 9, and 17 in Fig. 927, and are the smaller porcelain terminals in Fig. 894. In the right-hand section or "leg" of Fig. 927, it will be found that terminal 1 is joined through a section of the winding to terminal 2, which is the central terminal of the seven to which tappings are brought from various parts of the windings. These seven terminals are all arranged on one of the larger terminals of Fig. 894, and a seperate view on a larger scale of one of these terminals is given in Fig. 928. Six tappings, 3 to 8 in Fig. 927, are arranged round the central terminal 2, and any one of these six tappings, but only one at time, can be joined to 2 by the link shown as joining 2 and 3. The standard change in the number of turns in the leg as successive sections are brought in or out by connecting the successive taps is $2\frac{1}{2}$ per cent., provided that the leg voltage does not exceed 20,000; in other words, the maximum voltage between successive terminals on the insulator shown in Fig. 928 is not to exceed 500 volts.

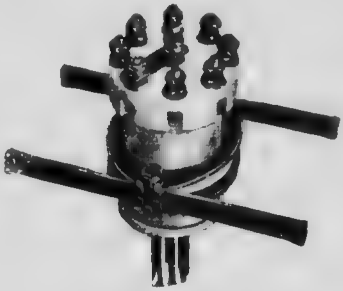


Fig. 928.—Ferranti Special "Tapping" Insulator.

An important feature of the scheme shown in Fig. 927 is that the section of the winding connected to the "line" terminal is always the same, and that none of the tappings is directly connected to line. This means that only the two end sections of the winding need be specially insulated to protect the leg from surgings. If this "buffer" section were not interposed, every section to which a tapping is connected would have to be specially insulated and mechanically strengthened to protect it from the effect of surges.

It will be noted that, as in a previous case, the different tappings are not brought to external terminals, and that therefore the change-over from one tap to another cannot be made by switches external to the transformer tank. In fact, to change a tapping, the top of the transformer tank and the float have to be removed, and, since the terminals shown in Fig. 894 are all below the top level of the oil, either the transformer must be partly lifted out of the tank or the oil partly drained off before a link can be changed. All this, of course, is deliberately planned. It is not intended that a change should be made easily, as such changes should not be required often in actual practice. The best tapping for the particular service should be ascertained when the transformer is first brought into commission, and the links connected accordingly. Only a serious change in the conditions should necessitate changing the positions of the links, and this change can then be made with due care and with the transformer "dead."

Terminals.—The electrical connections between the outside and the inside of a transformer tank are made in various ways, so as best to meet the requirements of good insulation and provide security against leakage of oil. Two general methods may be cited. In one flexible conductors, ending externally in themselves or in other connectors, are attached to the real terminals on the transformer itself inside the case, and are brought out through carefully designed and insulated bushings. Examples of such methods appear in several of the illustrations given in other sections.

The other method is to provide a carefully designed terminal on the cover or other convenient part of the tank, and to this terminal the external conductor can be attached. Many different patterns have been worked out for such insulated terminals, and it need scarcely be said that the voltage to be insulated profoundly affects the design. One or two examples here will suffice for our purpose.

The terminals for external circuits used in the Ferranti transformers described elsewhere are of the second type, inasmuch as they consist of porcelain bushings in the top of the oil tank, as can be seen in Fig. 939. Fuller details of these terminals are shown in Fig. 929, which is an end view, partly in section, of one of the limbs of a three-phase transformer. The bushings, as they appear from the outside, are shown in Fig. 940, from which, as well as from Fig. 929, it will be seen that the radiating corrugations are modified to make room for them, and in Fig. 929 they are shown as further protected by overhanging eaves, which do not appear in Fig. 940. The bushings are placed below the oil float described elsewhere, and their inner ends are therefore immersed in insulating and cooling oil. They consist of cylindric masses of porcelain, thickened near the middle for attachment to the side of the tank, and slightly taper toward each end. The conductor passes through the hollow axis of the cylinder, and oil-tight packings are firmly clamped on the ends by nuts and locknuts, which also serve to clamp the thimbles into which the inside and the outside conductors are to be sweated. One of the internal tapping insulators, of which a photograph has been given in Fig. 928, is shown at R, and the multiple cable passing down to the coils can be traced. The single cables passing down from the inner ends of the insulating bushings to the transformer coils are kept in their places and protected by insulating tubes until they reach the level at which they make connection with the coil conductors. A low-voltage connection, probably for the neutral conductor ("star" winding) can be observed at the bottom left-hand corner. Other details of this drawing are referred to elsewhere (*see* pages 871 and 904), but it may be repeated here that none of the internal conductors rise above the level of the insulating oil.

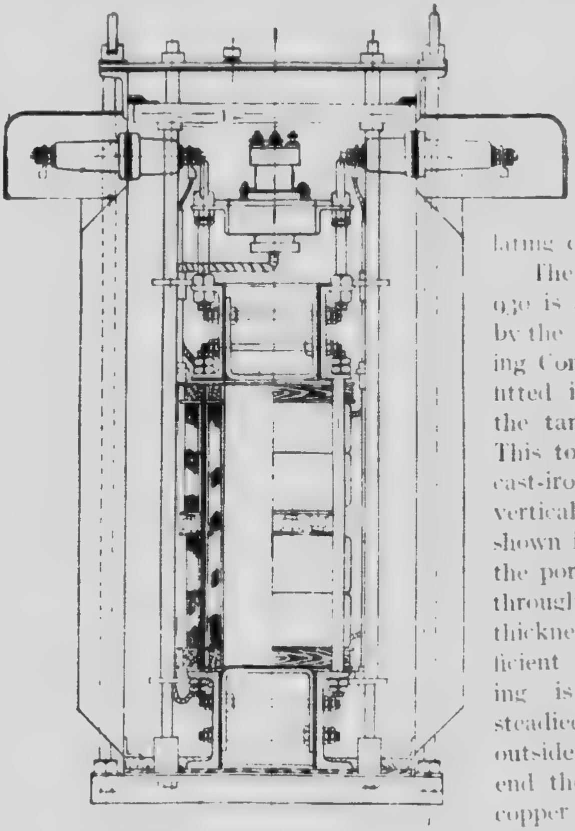


Fig. 929.—End Elevation (half in section) of Ferranti Transformer

The terminal shown in Fig. 930 is a "box terminal" designed by the Brush Electrical Engineering Company, and intended to be fitted in the side of the top of the tank illustrated in Fig. 943. This top, it will be noted, is of cast-iron and is fairly deep in the vertical direction. Part of it is shown in section in Fig. 930, with the porcelain bushing B B passing through the vertical web. The thickness of the web being insufficient for the purpose, the bushing is further supported and steadied by the rings R R on the outside of the web. On its inner end the bushing is pierced by a copper terminal bolt C, which can be clamped in position by the nut *n* and washer *w*, by which the expanded thimble T at the end of the bolt can be drawn against the porcelain shoulder. The bolt is prevented from turning in the insulator by the pin *p*. The other nuts N N N are for clamping the conducting strips coming from the transformer. The external conductor is obviously to be sweated into the thimble. A long length of protected leakage surface is provided, but as the fitting is intended for comparatively low voltage, the porcelain is not corrugated

Full details of the terminals and their connections inside the tank are given for the Johnson and Phillips transformer in Plate XIV, and the difference in design between the low- and the high-voltage terminals should be noted. The differences appear more clearly in Figs. 631 and 632, which show the terminals separately on a larger scale [illegible]. In the high-voltage case (Fig. 632) each insulator is a hollow porcelain cylindric insulator not quite 9 in. long, cemented [illegible] ring *r r*, which can be clamped to the top of the case [illegible] down the removable cover *c* which provides access to the [illegible] clamping spindle *s* (Plate XIV.). Whilst, however, the greatest diameter of the high-voltage insulator *h h* (Fig. 632), which has to stand a working voltage of 5,500 volts, is 5 in., that of the low-voltage insulator *l* (Fig. 631), which has only to stand 625 volts is only 4 in. Moreover the corrugations of *h h* are more numerous than those of *l*.

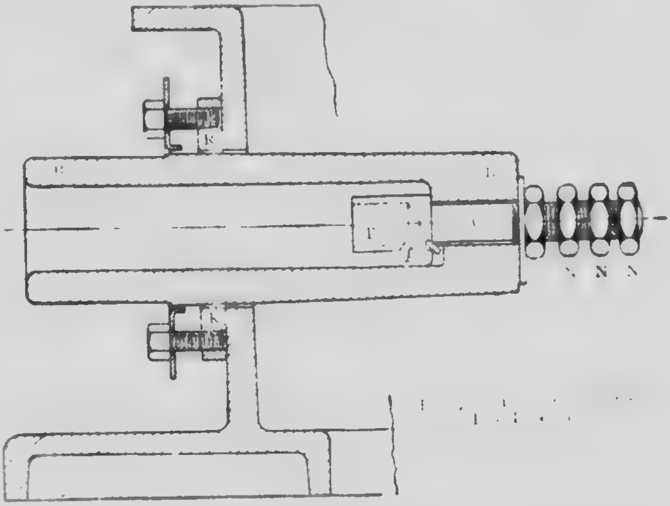


Fig. 631.

The conductor *c* passing through *h h* is a copper stem *k*, ½ in. in diameter and about 12 in. long, screwed at each end to carry the nuts shown. As an additional insulating precaution a micanite sleeve, with a shoulder at one end and a flange ring at the other, is slipped over the copper. The stem *k* is connected to the conductor A, which comes from one corner of the high-voltage mesh winding by the twenty very thin strips of [illegible] copper ¾ in. wide. The conductor A is enclosed in a "[illegible]" tube which is held in position by clamps. The wide air space, nearly 2 in. in diameter, between the micanite and the porcelain should be noted: there is no such space in *l l*.

On the low-voltage side a more substantial stem K, ¾ in. in diameter passes through the insulator, the current on this side being 177 amperes against 13 amperes on the high-voltage side. No micanite sleeve is slipped over K, but its method of connection to the transformer lead is similar to, but more substantial than, that already described, the twenty flexible copper pieces being 1½ in. wide and each 11 mils thick.

Clamping of Coils. Next in importance to careful design and workmanship in the connections and terminals is the necessity for very firm anchoring of the coils in their positions. With the large transmission systems now common, in which thousands of horse-power are being handled, it is possible to concentrate on a single transformer large mechanical forces caused by sudden surges due to some breakdown of insulation or other defect in the neighbourhood of the transformer or in the transformer itself. Such surges or short-circuits may pass momentarily through the transformer enormous currents hundreds of times above the normal, and these currents develop very large mechanical forces between the coils and the magnetic circuit and between the coils themselves.

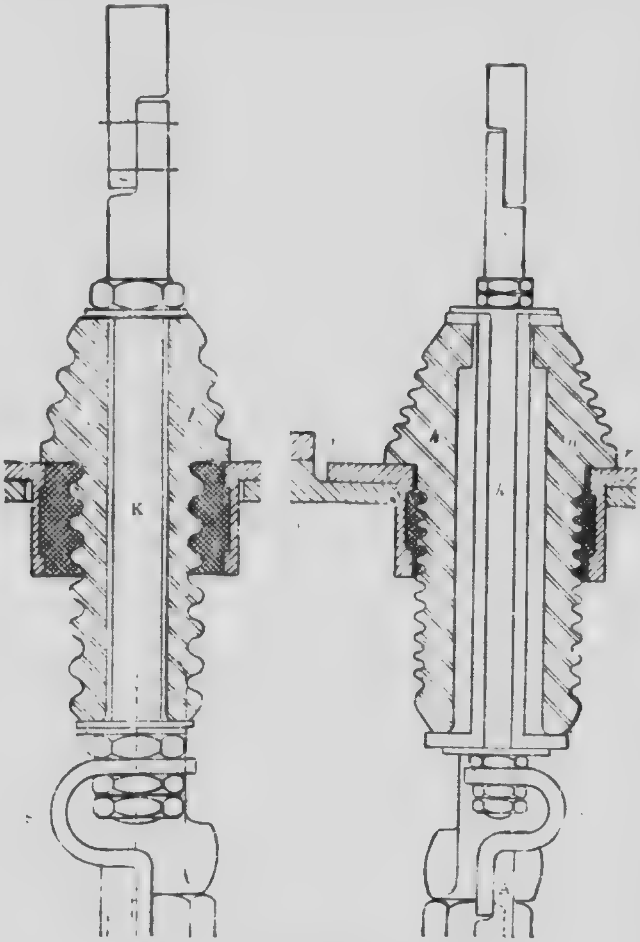
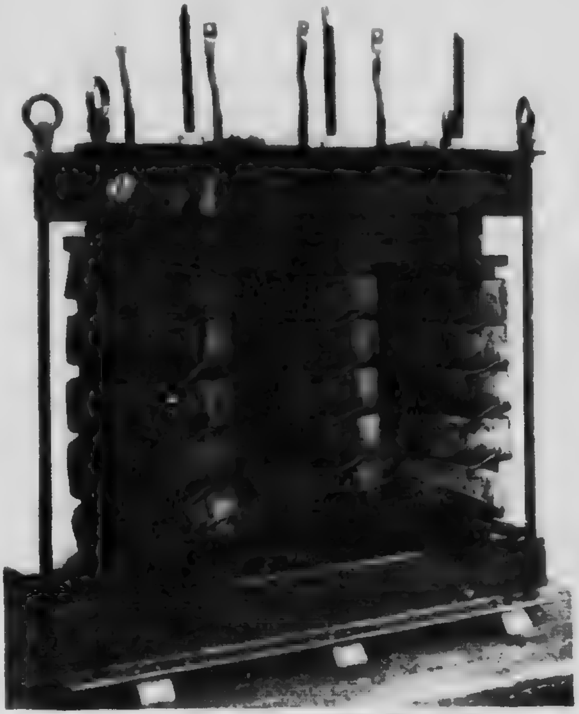


Fig. 531. Fig. 532.

Types of High Voltage Transformer Terminals.

In this connection it should be remembered that conductors carrying currents circulating in the same direction are attracted and tend to draw together, whilst conductors carrying currents in opposite directions are repelled, and tend to be forced apart. The laws of the mechanical interaction of co-axial coils carrying such currents have been fully explained elsewhere in this book, and as a consequence of these laws it follows that in the case of a heavy surge the conductors of contiguous coils of the same circuit of a static transformer compress themselves together, but the primary and secondary coils repel one another. In the case of the short circuit of a primary coil inside the transformer, the short-circuited portion acts as a secondary coil, and its conductors tend to move away from the other windings of the primary.



[illegible] 933.—D[illegible] Transformer [illegible]

That the danger is not an imaginary one, and that very large forces may be developed, will be realised by an inspection of Figs. 933 and 934, which are reproductions from photographs kindly placed at the author's service by the courtesy of Messrs. Ferranti, Limited. The transformer was not a very large one, its capacity being 150 *kv.a.* at 25 periods three-phase, the voltages being 5,000 and 400 volts on the high and low sides respectively. The photographs show a displacement of the [illegible], which in view of the solid construction of the transformer is almost [illegible]. On the occasion when this displacement occurred the transformer had only been switched on for a short time when a short circuit occurred on the low-voltage circuits external to the transformer. Curiously enough, the mischief arose in three over-potential safety devices placed in the mains for the very purposes of protecting the transformer. A short-circuit occurred in these devices, the duration of which as an exceptionally serious fault must have been very brief, for w[illegible] transformer was immediately switched on again o[illegible] the tripping gear operated quite comfortably, and opened the high-voltage switches. What was left of the short-circuit was then removed, and when the transformer was next switched on it was found to be electrically quite in order, and withstood an insulation test of 8,000 volts. Without being further examined, it was put on load again and was used in the condition shown in the photographs for three months. When returned to the factory and tested it was found that the iron and copper losses were exactly the same as when it was originally sent out.

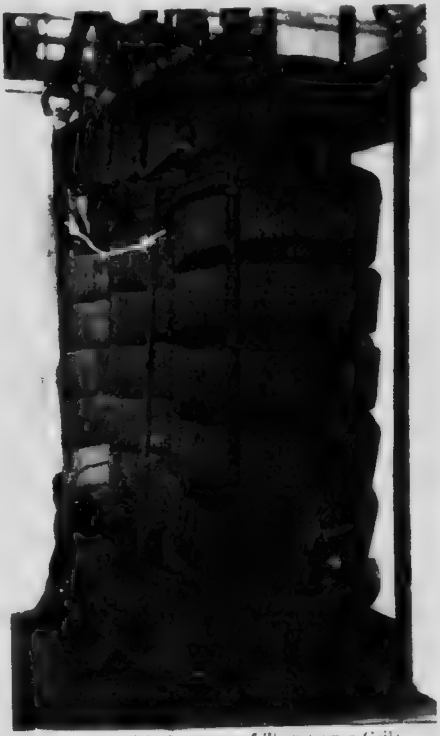


Fig. 934.—Displacement of Transformer Coils.

With this concrete example before us it will be interesting to examine what is now done, in the light of such experiences, to clamp the coils more firmly.

In their most recent transformers which are likely to be exposed to contingencies which may produce the results just referred to, Messrs. Ferranti have introduced, half-way down the limbs in the high-voltage belt, what may be described as elastic shock absorbers in the form of coiled springs made of flat strip. The position and shape of these springs can be seen in Fig. 929, which, as already explained, is a view half in section of the end limb of a three-phase transformer. Two of the springs are shown in the full end view on the right, and one in the half section on the left. From the latter it will be noted that the springs are inserted outside the insulating shield which divides the low-voltage inner coil from the encircling high-voltage outer coils. Should the latter be forced apart, as in Figs. 933 and 934, these springs will take up at least part of the sudden shock, and partly, if not wholly, restore the coils to their original position when the shock has passed.

In the *Brush Transformer* (Fig. 895) it will be noticed that there is a gun-metal casting on the top of the high-voltage windings which is clamped to the web of the lower channel iron by long bolts which run down the outside of the windings, six for each plate. The bolts are pro tected by insulating tubes, and securely hold the windings against any tendency to horizontal motion by means of long insulating packing pieces. Vertical slackness can be taken up by means of the nuts and lock-nuts on the top of the clamp, and if deemed necessary strong springs can be fixed underneath these nuts to take up automatically any occasional slackness. The low-voltage windings are separately clamped by gun-metal rings held down by pinching screws.

The above shows the application of clamps to "concentric" windings. The principle of a coil-clamping device applied by Messrs. Johnson and Phillips to "sandwich" windings is given in Fig. 935, and an illustration of an actual application appears in Fig. 936. In Fig. 935, which is partly in section, one limb only of the three-phase transformer is shown. There is a bottom movable clamping plate B B, which is in three sections to allow of each set of coils being clamped separately. The top clamping plate T T is fixed, and extends over all the sections. On the top of the top core there is a thrust block K K, and through this, through the top clamping plate T T, and through the iron of the core clamps, the tension rods R R pass freely. The upper ends of these rods are bolted to the tension yoke Y Y, and through the middle of this yoke there passes a strong square-threaded screw S, which is prolonged into a clamping spindle C with a square end. When this spindle is turned so that the flat lower end presses on the centre of the thrust block K K it is obvious that the rods R R are thrown into tension and tighten up the bottom clamping plate B B, thrusting the coils against the top clamping plate T T. The arrow heads indicate the direction of the forces brought into play.

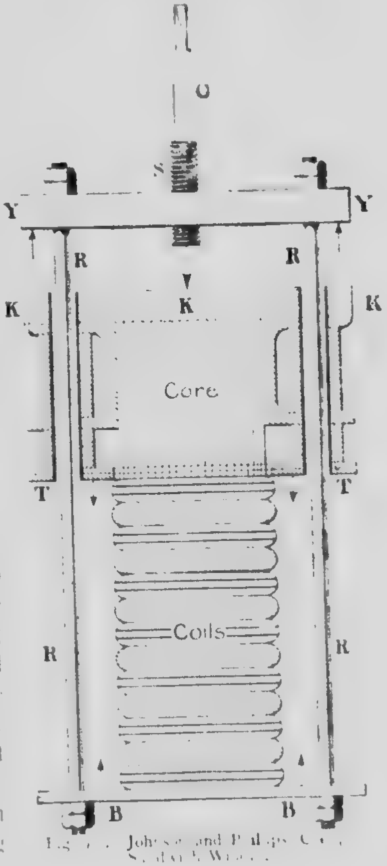


Fig. [illegible] Johnson and Phillips C[illegible] Sandwich Windings.

A transformer of quite recent design to which this clamping device has been applied, and which incidentally may serve as an example of a "core" transformer with "sandwich" windings is illustrated in Fig. 936. The various parts of the clamping device will readily be made out from the foregoing description. Where possible the same reference letters have been inserted. It is interesting to note that the ends of the clamping spindles are carried above the level of the oil, where they are lightly supported by the framework to which the leads from the windings are clamped. By screwing down these spindles any shrinkage of coils during service can be taken up without removing the transformer from its tank. The cradle by which the transformer can be lifted out of its tank is of simple construction, consisting only of two bottom cross-pieces and four vertical rods, supported as shown and ending in eye-bolts. These cradles also serve to clamp the yokes to the rest of the carcass.

It is obviously impossible, without unduly extending this chapter, to give dimensioned drawings of all the varieties of transformers, but it is perhaps desirable that one such drawing should be available for reference, and the above transformer has been selected for the purpose. By the courtesy of Messrs. Johnson and Phillips there are shown in Plate XIV. three views of the transformer with a sufficient number of parts in section to enable the reader to follow with actual dimensions the main features and approximately the details of the design. Fuller details of the terminal insulators have been already given in Figs. 931 and 932.

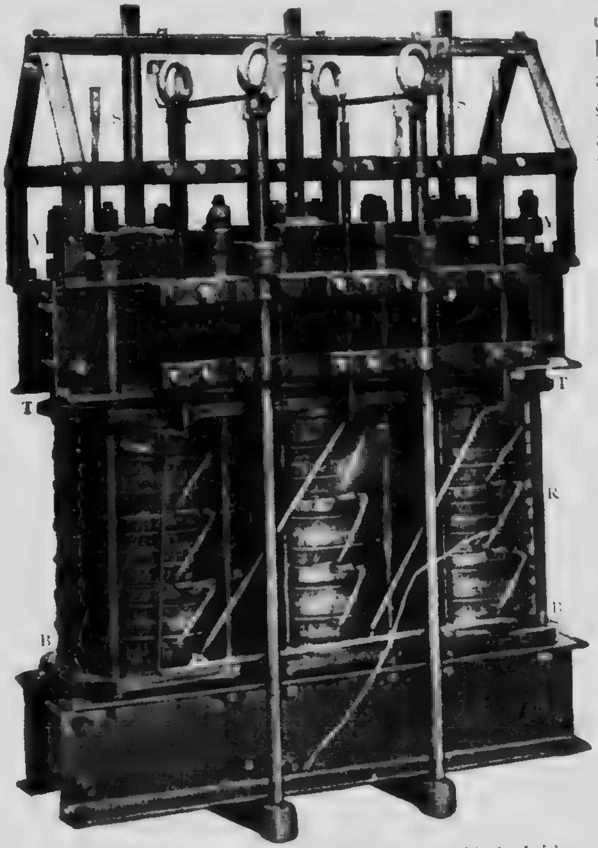


Fig. 936.—Johnson and Phillips' Core Transformer with Sandwich Windings and Special "Clamping" Device.

The transformer is three-phase, and has a capacity of 400 *kv.a.* at 40 periods, the voltages being 5,500 and 625 and the currents at full-load 42·7 and 377 amperes. The top left-hand drawing is a front vertical view of the transformer with the right-hand limb shown in section, thus giving

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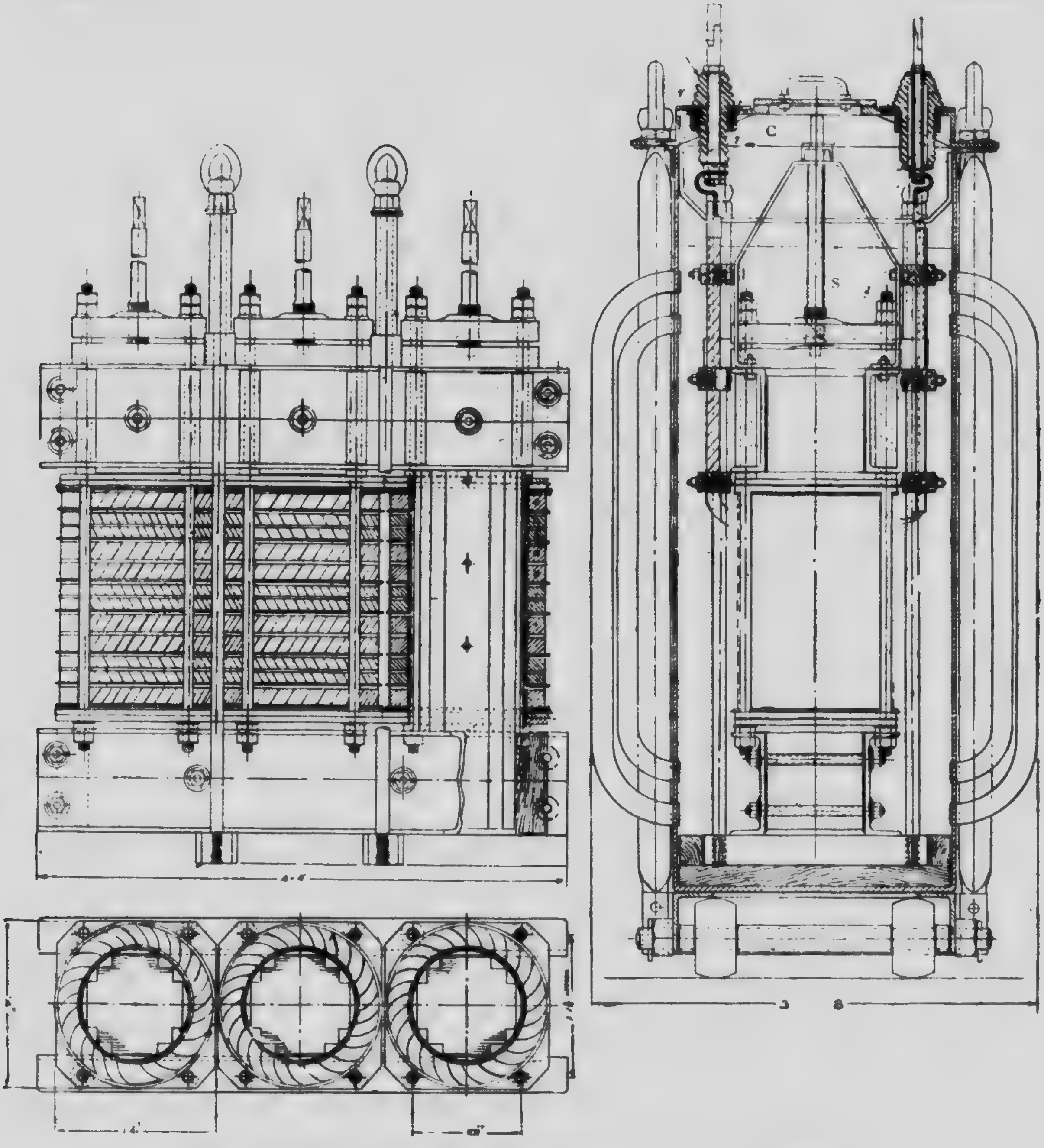


Johnson & Phillips' Three-phase Transformer, 400 *kv.a* at 40 Periods.

page 913.

with the bottom left-hand drawing, which is a horizontal section through the three limbs, full details of the magnetic circuit. The material used is stalloy, 14 mm. thick, the bottom yoke being interleaved and the top yoke butt jointed, this being rendered necessary because of the clamping arrangements.

The space occupied by the electric circuits is shown in section, the high- and low-voltage windings being distinguished by the letters H and L. For the high-voltage circuit there are two complete and two half-coils (at top and bottom) H per limb, all these being in series. For the low-voltage circuit there are three complete coils L per limb, connected in parallel. Each H and each L coil is split into two sections, one wound normally and the other in the reverse direction, so as to bring the beginning and the end of the winding both out at the outer periphery of the coils to avoid crossing of connections. Each low-voltage half-coil consists of 18 turns in 18 layers of one turn each; thus the voltage between layers is never more than the voltage per turn, which in this case is 10 volts, quite a safe and readily insulated voltage. The high-voltage coils on the separate limbs are "mesh" connected, and the low-voltage coils "star" connected, with the neutral point earthed as required by the Board of Trade regulations, the transformer being for use in a colliery.

A pergamite cylinder, 265 mm. in internal diameter and 7 mm. thick, is slipped over the core iron, from which the coils are further separated by pergamite right-angle collars, these collars serving, with additional insulating packing, to separate the H from the L coils. Further insulation is provided, top and bottom, by micanite rings 1·5 mm. thick, bedded on leatheroid rings 0·5 mm. thick, interposed between the extreme coils and the clamping plates. For cooling purposes notches 2 in. wide by ¾ in. deep are provided top and bottom. The clamping plates are ½ in. thick, there being one pair for each limb at the bottom and one long pair for the three limbs at the top. They are slotted on alternate sides on the centre line of each limb, so as to diminish eddy currents. The outside dimensions of the transformer without its tank are 5[illegible] in. long by 22 in. wide by 70 in. high to the top of the lifting eye-bolts.

The right-hand drawing shows additional details of the clamping arrangements, of the high-voltage and low-voltage terminals and of the tank. The clamping arrangements need not be further described, as reference can also be made to the diagram in Fig. 935, and the terminals and details of connections which are dealt with on page 908.

An outside view of the tank is given in Fig. 937. It is made of ⅜-in boiler plate, and is of the type which uses vertical oil circulating and radiating tubes, of which there are two rows on each of the four sides. The tubes, which are made of steel and are 2 in. in diameter, are 96 in number. The inside dimensions of the tank are 54 in. by 27 in. by 77 in. high, but the extreme measurement over the pipes is 72 in. by 44 in. approximately. The overall height to the top of the terminals is 8 ft. The value of the addition of the radiating pipes on the cooling of the oil can be inferred from the fact that the radiating surface of the tank sides is about 67·5 sq. ft., and that the radiating surface of the tubes is 252 sq. ft., or nearly four times that of the sides of the tank. The permissible temperature rise is 40° C., the iron losses being 2·8 kilowatts and the copper losses 4·2 kilowatts at full load. If there were no other radiating surfaces this would mean a radiation of 22 watts per square foot, a figure well within the range of ascertained emissivities, for a maximum temperature rise of 40°. At the left-hand side of the tank in Fig. 937 there will be noticed a pocket *p*, through which a thermometer can be introduced into the tank.

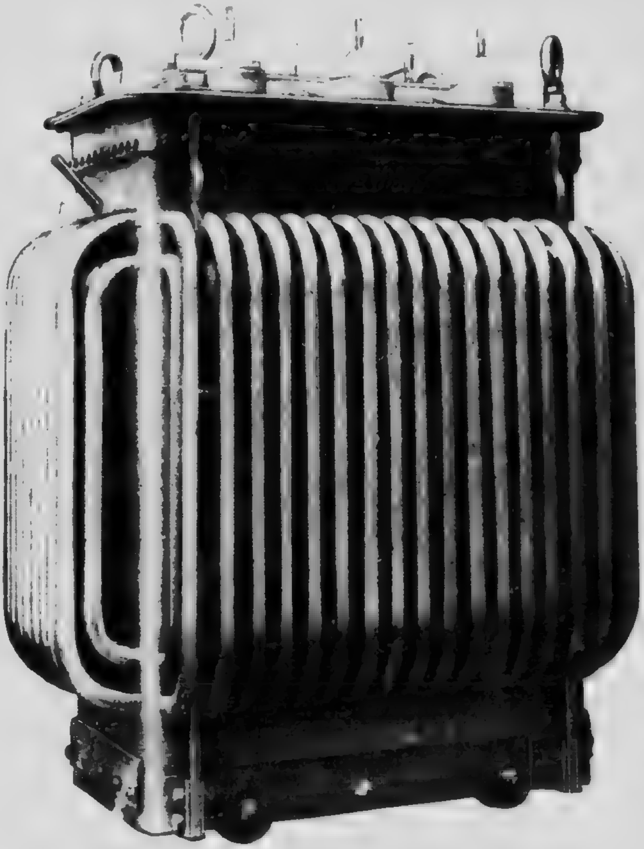


Fig. 937.—Johnson and Phillips Transformer Tank with Radiating Pipes.

In conclusion, it may be of interest to note that the transformer weighs 5,600 lb., the tank 2,240 lb., and the oil (300 gallons) 2,570 lb., the total weight being thus 10,410 lb., or between 4 and 5 tons. The transformer is so bolted to the tank that the whole can be lifted by the eye-bolts seen in Fig. 937. The lifting bolts to which these eye-bolts are attached are made of forged steel, and are of ample strength for the weight to be carried. The whole transformer is designed to withstand the rough handling which so often is accorded to such equipment in a colliery.

VII.—THE COOLING OF TRANSFORMERS

As with other machinery and apparatus used in heavy electrical engineering, the load which a static transformer can carry depends in the first place upon the maximum temperature at which it is permissible for it to work. The principles and considerations limiting this temperature have been more than once referred to in the preceding pages, and have led to the acceptance in modern practice of a temperature rise in British built transformers of 50° C. or 90° F. as being about a reasonable limit. On the Continent a greater rise, about 60° C., is frequently allowed, whilst in the United States the limit is usually lower, being between 35° and 40° C. In dealing with the causes which affect the temperature of the static transformer the general conditions are fairly simple. The total heat produced in a given time is a measure of the capacity and the efficiency, or, more correctly, the *inefficiency*, of the transformer. As the heat is produced in the copper and in the iron according to laws which have been carefully investigated, the calculation of its rate of production, as shown elsewhere, is a comparatively easy matter. There is nothing of the nature of the friction of bearings, windage, or any of the other disturbances caused by the motion of masses of materials to complicate the calculation. The rate at which the heat can be dissipated or got rid of depends upon the arrangements made with this object, which we shall now describe. It is obvious that the more rapidly the heat can be abstracted the more rapidly may it be produced and, *cæteris paribus*, the larger the load which can be placed upon a given transformer.

The method adopted for cooling the transformer has been suggested on page 864 as one of the bases of classification, and it is a basis which has much to recommend it. The methods there enumerated fall into two broad types, namely (i.) those in which the only facilities provided are those which are inherent in the particular design in which the necessity for facilitating the passing away of the heat by conduction, radiation and convection have been steadily kept in view, and (ii.) those in which additional heat carriers are deliberately introduced to expedite the dissipation of the waste heat produced in working the transformer. In this section we shall follow the classification set out on page 864.

Transformers Air-cooled by Ordinary Radiation. The great majority of small transformers fall into this class, and the modifications in design intended to facilitate the conduction of the heat from the place where it is produced to the radiating surfaces have been indicated in the descriptions of particular transformers. In some of these the design aids the circulation of the cooling fluid, air or oil, through the body of the transformer, and this facilitates the cooling without any trouble to those in charge.

Where the transformer for reasons connected with its use has to be either "semi-enclosed" or "enclosed," (see pages 864 and 865), the enclosure is frequently designed to assist the radiation of the waste heat. Thus the enclosing box or tank, when the transformer and the amount of heat to be dissipated are small, may have a smooth surface, as this is the cheapest to make, but the surface may be semi-corrugated or fully corrugated for larger transformers. Illustrations of these various types appear elsewhere.

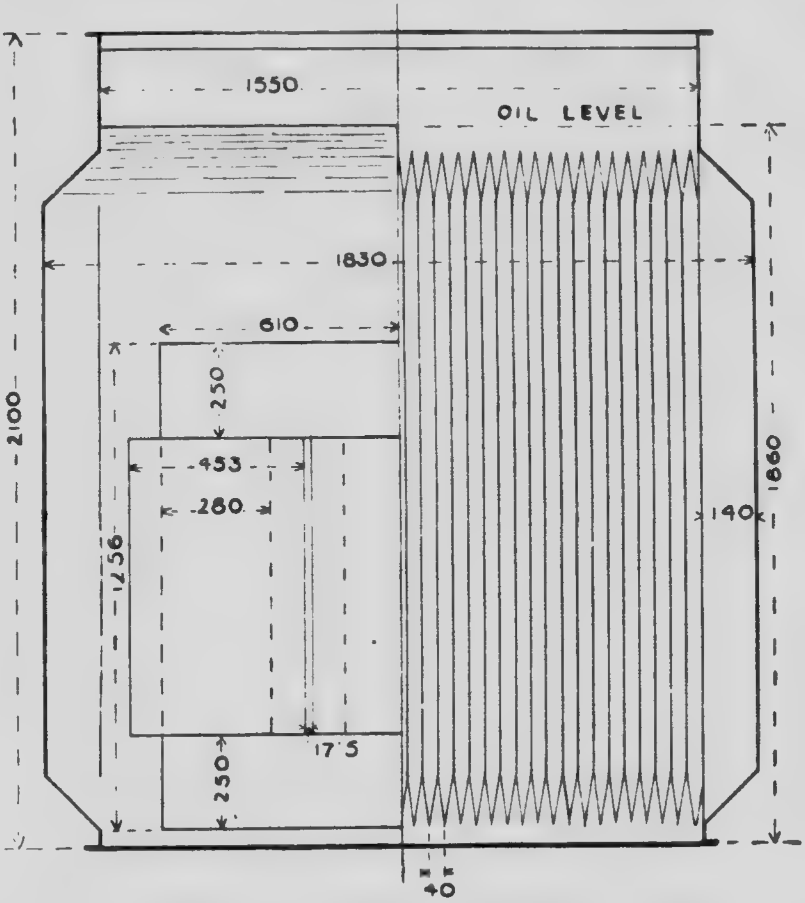


Fig. 938.—Design of a 1,000-KV.A. Transformer Tank (dimensions in millimetres).

Oil-immersed Transformers.—Somewhere about 1890, the device of immersing the transformer in a bath of insulating oil was introduced, partly to improve the insulation in keeping moisture from the textile materials used to insulate the copper, and partly to prevent the breakdown of the insulation by high-voltage lightning discharges. If such a discharge takes place in oil then in many cases the oil will rapidly quench the spark before the damage has become serious, and flowing into the space where the spark occurred will automatically restore the insulation. In practice, however it was soon found that the presence of the oil lowered the temperature of the transformer or allowed the transformer to take a heavier load without exceeding the scheduled temperature. This is because the thermal capacity of oil per unit volume is very much higher than the thermal capacity of air, the ratio being about 1,300 to 1. Little or nothing is known about the transfer conductivity under the conditions of transformer working, but assuming that there is no great difference, this means that by its higher thermal capacity the oil will take more heat to bring its temperature up to the limit. In the meantime, however, being a fluid like air the warmed oil floats upwards and comes into contact with the walls of the tank, giving up part of its heat, which is conducted to and radiated from the exposed outer surface of the tank. Anything, therefore, that will tend to promote the circulation of the oil inside the tank and to radiate the heat from the outside will tend to raise the working capacity.

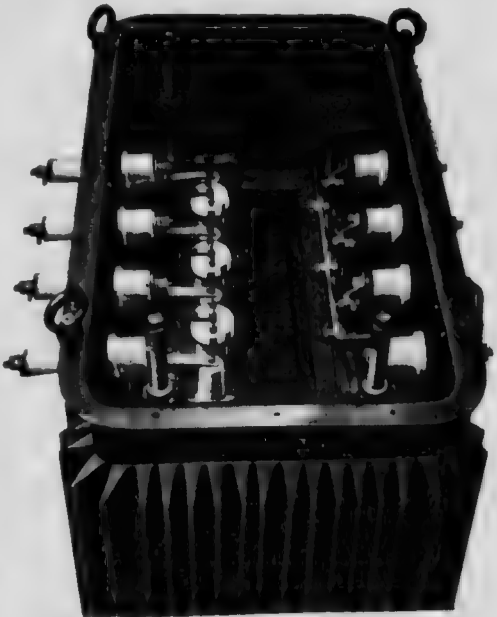


Fig. 939.—Top of **Ferranti** Transformer Tank before Oil is Filled In.

Excess Height of Tanks.—One simple method of increasing the facilities for cooling whilst securing other advantages to compensate for the increased over-all dimensions is to make the tank of a vertical height much greater than that of the actual transformer, thus providing an upper chamber which allows a greater quantity of oil with a corresponding increase of thermal capacity to be used, and in which the heated oil can collect clear of the working parts of the transformer. A comparison of the heights of the Johnson and Phillips' transformers shown in Fig. 885, with the heights of the tanks in which they are to be immersed, shows the extent to which this principle is carried in some modern air-cooled oil-insulated transformers.

Fuller details of these tanks, with actual dimensions, are given in Fig. 938.

which is a skeleton drawing of a tank, half in section, for a 1,000-*k*V.A. three-phase transformer. The outline of the transformer and its principal dimensions are also given. It will be noticed that whilst the over-all height of the transformer is 1,256 mm., the over-all height of the tank is 2,100 mm., an increase of 67 per cent. This allows for a depth of 1,800 mm. of oil, which is nearly 1½ times the height of the transformer, and calculation shows that the volume of oil for which space is thus provided is about five times the volume of the transformer. The tank is 980 mm. wide, measured to the extreme limits of the corrugations.

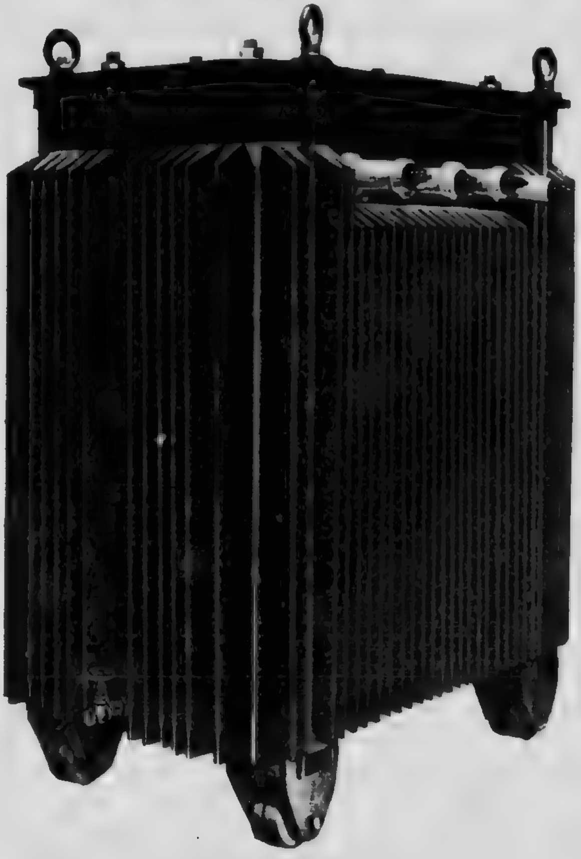


Fig. 940.—Oil-Tank for Ferranti Three-phase Transformers.

Incidentally this increase of top space enables the terminals, as well as the coils and cores of the transformers, to be immersed in the oil, and secures for them the advantages of oil insulation. A perspective view from above of one of the Ferranti transformers, in which these advantages are secured, is shown in Fig. 939. This shows the top of the transformer, the coils of which were illustrated in Fig. 894. In this case the level of the top of the oil is above that of the exits by which the leads leave the transformer case, which necessitates these exits being very carefully bushed to prevent leakage of oil. For this purpose oil-tight porcelain bushings as shown are used, and thus every part of the electrical circuits within the tank is oil insulated.

An external view of the oil tank, showing the high-voltage terminals emerging through the porcelain bushings, is given in Fig. 940. The tank illustrated is for the 200-*kv.a.* size described on page 871; it is 50 in. long, 40 in. wide, and 71 in. high.

An alternative method is to bring up from the terminals insulated leads to exit holes well above the level of the oil. This has the disadvantage that the oil, by the action of surface tension, may creep up the outside of the leads and, by a siphon action leak through the exit holes, causing much trouble and annoyance as well as wasting oil.

For reasons to be given later it is desirable that the heated oil should come into contact with air as little as possible, and therefore when the transformer shown in Fig. 939 is filled with oil a wooden slab is floated on the top of the oil, as shown in Fig. 941, which is a top view of the same transformer showing the float in position. The float, pierced only with holes for the clamping bolts, covers very nearly the whole internal cross section of the tank, and, of course, sinks a certain depth into the oil. Thus only a comparatively small proportion of the surface of the oil is exposed to the atmospheric air in the clearance at the top of the tank.

[illegible] Tank with Float in Position.

Having thus placed the transformer in a vessel full of oil, the general effect will be that, when the transformer is at work, the oil in contact with the coils and core of the transformer in the middle of the tank becomes heated, expands and rises to the top, its place being taken by cooler oil drawn from the bottom and sides. At the top it becomes partly cooled, flows laterally outwards by the circulation set up, and descending along the cold vertical sides of the tank is still more effectively cooled and made ready to pass again through the working transformer to take up more heat.

Radiation Facilities.—It therefore becomes important to promote in every way the cooling of the hot oil while thus circulating, and the easiest method of doing this is to increase the radiating surface of the vertical sides of the tank, which is the effective vehicle for the removal of the heat.

The increase of surface is very simply obtained by corrugating the sides as shown already in several of the preceding figures (Figs. 888 and 940) and in more detail in Fig. 938, which is a vertical sketch, and in Fig. 942, which is a horizontal sketch, half in section, of a Johnson and Phillips' tank. The corrugations in Fig. 938 have a pitch of 40 mm., and a depth of 140 mm.; the increase in the surface in contact with the oil and of the external radiating surface is therefore approximately from 40 to 280, or from 1 to 7, thus enabling the sides of the tank to dissipate about seven times the heat which an uncorrugated tank could dissipate.

As a final example of this type of tank, Fig. 943 shows the standard type for large transformers manufactured by the Brush Electrical Engineering Company, described at page 872. The corrugated body is of sheet steel which is carried by and welded to the bottom cast-iron tray. To strengthen and protect the bottom welds the tray is filled with cement. The top of the body is covered as shown by a heavy casting, which is cross-strapped to the bottom casting as shown and is covered by a sheet iron lid [illegible] inch thick. The cross-straps stiffen the tank and allow the transformer, which when filled with oil, weighs 20,500 lb. for the 600-*kv.a.* size, to be lifted by the eyebolts without risk of distortion. Each eyebolt is screwed to a long wrought-iron rod 1½ inch in diameter and over 9½ feet long, which passes vertically down between an outside fold of the corrugations and through the bottom of the tray, to which it is securely bolted. The tank is 84 inches long and 44 inches wide, measured over the corrugations, and is 117 inches high from the bottom of the tray to the top of the eyebolts.

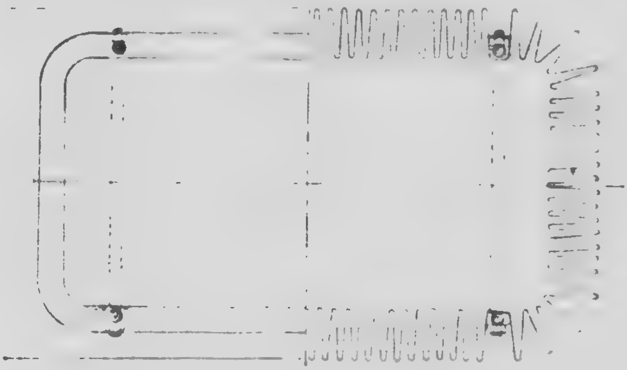


Fig. 942.—Skeleton Sketch (half in section) of a Transformer Tank.

Attention should be called, both in this and in other tanks illustrated (Figs. 890 and 940), to the drain cock *c* at the bottom of the tank, by which the oil can be emptied out of the tank, and to the glass gauge *g* at the top, by which the level of the oil inside the tank is indicated. The leads are brought out through bushed openings on the far side.

In some designs of transformer tanks a vertical baffle plate is provided behind the corrugations to direct the descending oil against the corrugated sides, and thus to secure more effective cooling

There are other methods than those shown of constructing transforme tanks and increasing the radiating surface [illegible] not allow of their description in detail. [illegible] with ribs, either as part of a casting or attached [illegible] Then again the corrugations may be formed [illegible] ations illustrated above may themselves [illegible] still further the radiating surface. [illegible] external radiating boxes may be provided [illegible] being a development of the baffle [illegible] mentioned above.

[illegible] method of obtaining [illegible] radiating surface, of which [illegible] example has been already given [illegible] may be still further illustrated here. It consists of fitting to a tank external cooling tubes [illegible] is shown [illegible] Fig. 644, which represents such [illegible] of both [illegible] manufactured by the Br[illegible] [illegible] that [illegible] that the [illegible]ency of this type of tank is higher than that [illegible] is obviously more expensive, for the tubes [illegible]d into [illegible] side of the case so that a perfectly [illegible] obtained. Boiler-plate tanks are also constructed [illegible] pipes. Their cost is higher than sheet-steel tanks, [illegible] what stronger and are preferred by some users on

43.—Brush Standard Tank with Corrugated Sides.

this account, and also because the cooling action is regarded as more efficient.

Radiator Tanks.—In a still more recent development, applied to large transformers (*e.g.* 8,000 *k*V.A.), the circulating pipes are replaced by elaborately constructed radiators arranged either radially or tangentially round the tank, the oil circulating through these radiators in lieu of the pipes.

Sludging of the Oil.—One of the chief difficulties met with in the practical working of oil-immersed transformers is caused by what is known as "*sludging.*" This is a darkening and thickening of the oil, which more or less rapidly results in the deposition of a solid sediment on the windings and in the lower part of the transformer case. The cause of this decomposition is chiefly the chemical action of the oxygen of the air, an action which becomes more rapid as the temperature of the oil rises. It is also assisted by the presence of copper or lead, which seem to exercise what the chemist calls a "catalytic" action. Most, if not all, insulating oils are mixtures of hydrocarbons, composed of hydrogen and carbon only, and are liquid even at high temperature, eventually vaporising without decomposition as the temperature reaches the boiling point in each case. They are, however, liable to be oxidised if they come into contact, especially at a high temperature, with free oxygen as contained in the atmosphere, and the products of oxidation are often solid. If such solids are formed, they must eventually, as the oil circulates, be deposited as described above.

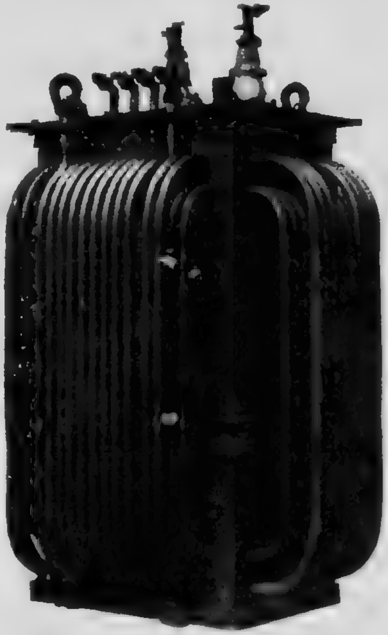
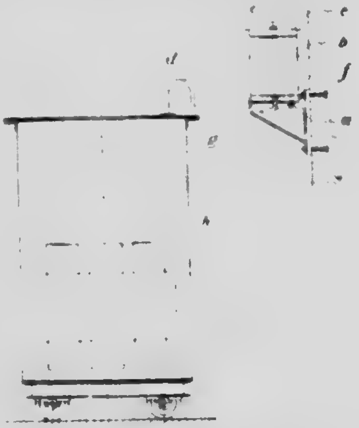


Fig. 944.—Westinghouse Transformer Tank with External Radiating Pipes.

It is, therefore, of primary importance to prevent, as far as possible, the hot oil coming into contact with the atmosphere. One method of minimising the area of contact, consisting of covering the surface of the oil with a float, has already been described on page 919. Another method shown diagrammatically in Fig. 945 is employed by Messrs. Siemens Brothers Dynamo Works, Limited, and transformers fitted with the apparatus are shown, under test, in Fig. 945. A little above the level of the transformer, when set up in its working position, there is erected a small closed expansion chamber *b*, connected to the space at the top of the transformer by a pipe *g* with an upward bend in it. The transformer is filled with the insulating oil, so that the connecting pipe is also filled with oil at the lowest temperature, which it reaches when not under load. When the transformer becomes heated whilst working, the oil expands, and the extra volume of oil flows into the expansion chamber without interfering with the circulation of the hot oil in the tank. Thus the oil in the expansion chamber is either comparatively or quite cold, and is practically unaffected by contact with the atmosphere. Moreover, only a small surface is exposed to the air in the expansion chamber, which is closed in and is provided with a safety valve *c*. When it is recalled that, in the example given on page 875, 2·45 tons of oil are used in the whole transformer, it will be understood how small a proportion of this has an opportunity of coming into contact with the troublesome oxygen.

This device also prevents the access of the moisture of the atmosphere to the interior of the transformer and its condensation in the tank. Arrangements are made for drawing off any water which may accumulate in the expansion chamber. The whole arrangement is so efficient that transformers provided with it have been run for from ten to fifteen years with the original charge of oil.



[illegible]

Another method of minimising the evils of sludging is to withdraw the oil periodically from the transformer, pass it through a filter press to remove any solid matter which may be in suspension, and then return it to the transformer. In many modern American stations quite elaborate arrangements are made for this purpose, the oil being withdrawn from the transformer and returned to it without disturbing any circuit or interrupting the service.

There is, however, a danger of overheating, due to diminished oil circulation, which may occur through a more or less serious breakdown caused by the failure of a pump or deposition of sludge in the pipes. This is safeguarded by the use of thermometers inserted in selected positions, and so constructed that if a dangerous temperature be reached they close a relay circuit and give a warning by bell or lamp to the attendant.

The effects and evils of sludging are graphically shown in Fig. 946, which is reproduced from a photograph sent to *The Electrician* in July, 1915, by Mr. Chattock, the electrical engineer of the city of Birmingham. It depicts a three-phase, oil-cooled, 380-*k*V.A. Westinghouse transformer which had been six years in service, for the last two years of which it had been run on full-load for between twelve and thirteen hours every day, transforming in this period approximately 7,500,000 units of electrical energy. Towards the end of the period the daily rise of temperature was observed to be increasing, and on withdrawing the transformer from its case the condition was found to be as shown. After being well cleaned and returned to the case with a charge of fresh oil, the temperature rise on full load, which had been 102° F. before cleaning, fell to 76° F.

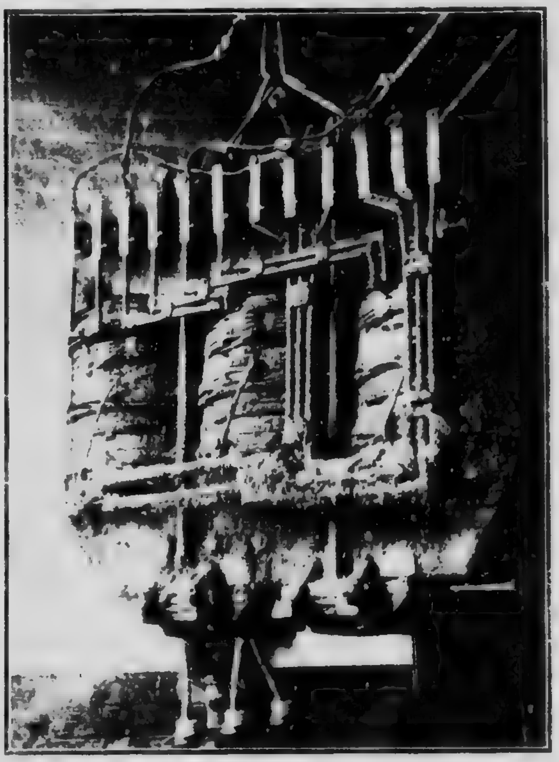


Fig. 946.—Transformer showing Effects of Sludging.

Incidentally, Mr. Chattock refers to the economy of using the more expensive white non-sludging transformer oil in preference to the ordinary and cheaper yellow variety. He found with the latter that sludging requires a change of oil every two or three years.

Choice of Oil.—In view of the above, it is obvious that the oil to be used should be carefully chosen. Vegetable oils quite fail to satisfy some of the chief requirements, and resin oils are also objectionable. The more important requirements may be summarised as follows:—

1. High dielectric strength.
2. High insulation resistance.
3. Freedom from moisture and from liability to absorb moisture from a damp atmosphere.
4. Absence of free acids and alkalies and combined sulphur.
5. High specific heat.
6. Low viscosity.
7. High flash point (say, 160° C.).
8. Low freezing or solidifying temperature.
9. Low volatility.

10. Constancy of composition in use.

11. Retention of above properties at all working temperatures.

The reasons for several of these requirements will be quite familiar to the reader of the preceding pages, but there are one or two new points. For instance, the *high specific heat* which for these mineral oils is about 0·48 to 0·51 (water = 1·0) ensures that the amount of heat absorbed in raising the oil to a given excess temperature shall be as great as possible. The *low volatility* means that the rate of evaporation shall be small; but, as is well known, this rate rises with the temperature. One of the tests sometimes specified is that the oil shall not lose more than 0·5 per cent. in weight whilst being exposed for eight hours at a temperature of 100° F. in an open vessel 3¼ in. long and 3 in. wide, the depth of oil being 2½ in. In actual practice the hot oil is in an enclosed space and the conditions for evaporation are not favourable. *Low viscosity* makes for mobility and facilitates circulation; the viscosity decreases as the temperature rises; on the other hand, a thicker oil may, as a rule, be safely raised to a higher temperature than a thinner sample.

The influence of a very small quantity of *moisture* on the specific resistance and the dielectric strength is very pronounced, but a subsequent increase in the quantity of moisture present is not so deleterious. The oil used should therefore be quite free from moisture, and it is considered that the electrical tests for specific resistance and dielectric strength are better indications of the absence of moisture than any of the usual chemical tests. An oil may be considered dry which has a specific resistance of 2×10^{12} ohms (centimetre measure), and which has a dielectric strength of 10,000 volts between a ½-inch disc and a needle point 0·1 inch apart, the tests being taken at about 15° C.

The formation of sludge appears not to affect the specific resistance or the dielectric strength or to depend upon viscosity or specific gravity. It, however, very much retards the heat transference, which is the main function of the oil, by forming a badly conducting layer on the windings and the exposed iron. It is highly desirable, therefore, that the tendency to form sludge should be as slight as possible.

With one exception, the requirements specified on page 924 can be satisfactorily tested before the oil is put into the transformer, but unfortunately the most important of them all, and the one for which some of the others are only introduced as leading up to it, cannot be very satisfactorily determined. This is the constancy, including freedom from sludging, of the oil under working conditions. The test usually employed is to heat the oil to a little above the maximum working temperature of the transformer in a glass vessel and to pass air, or, better still, pure oxygen, through it steadily, for forty to fifty hours. The test is made more severe if copper, with a specified amount of surface exposed, be immersed in the liquid, and still more severe if ozone be used instead of air. Any decomposition products which are formed during this test will also be produced in the transformer under working conditions. The products are separated and quantitatively estimated by ordinary chemical methods. It is satisfactory to know that oils are obtainable which under the above test form no appreciable solid matter or soluble acids. The limit supposed to be allowable is 5 parts in 10,000.

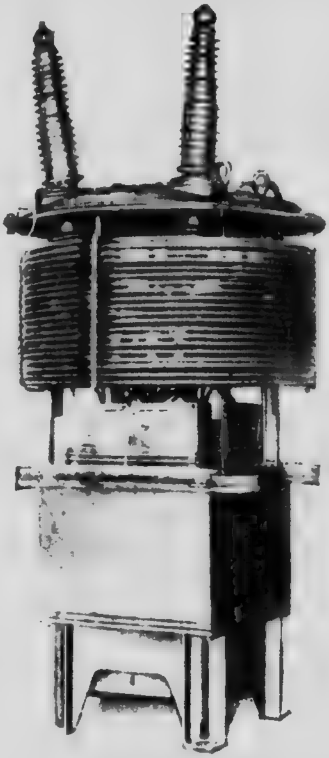


Fig. 947.—G.E. Water-cooled Transformer without Tank.

Water-cooled Transformers.—In water-cooled transformers, which are always oil-insulated, the greater part of the heat is carried away by water which is passed through a coiled pipe placed in the oil at the top of the transformer case. The circulation of the oil is much the same as in air-cooled transformers, the hot oil rising from the heated core and windings through ducts provided for that purpose, and completing its circuit by descending along the sides of the case.

Such a transformer removed from its case is shown in Fig. 947, which represents the interior of a 3,000 *k*V.A., 88,000-volt transformer, built by the General Electric Company, of Schenectady. The transformer itself is of the shell type, and the cooling coils are placed above it inside the case as shown. Through these coils, which when the transformer is on load are placed in the hottest part of the oil, cooling water is forced, which, absorbing the heat, carries it away. The arrangement is so effective that very little heat need be dissipated from the exterior of the tank, which is therefore, as a rule, not corrugated. The tank is built of heavy boiler-plate iron riveted to a cast-iron base, all joints being made absolutely oil-tight.

It should be noted that the transformer illustrated is of large capacity, 3,000 *k*V.A., and that therefore the heat to be dissipated at full load is very great, being at unit power factor 60 kilowatts, or 80 H.P., if the efficiency be 98 per cent. It is, of course, easy to calculate how much water must be supplied per hour to carry off this waste heat with a given rise of temperature.

Where water is not always available or perhaps desirable, as for instance in mountainous districts with severe winters, or where the cost of cooling water is excessive, corrugated tanks are used so that on an emergency air-cooling may be employed. The capacity of such a transformer when air-cooled only is about 70 per cent. of its capacity when water-cooled.

These and similar air-cooled transformers, manufactured by the same firm, are so constructed that the complete core and coils with the cover and leads can be lifted out of the tank as a unit. Eye-bolts are provided for this purpose as well as for lifting the entire transformer when filled with oil. Minute inspection of any part of the transformer may therefore readily be made with only the expenditure of time necessary to raise the transformer from the tank. If changes in the connections are all that is required, the transformer need only be lifted sufficiently to clear the terminal board of the oil when openings in the cover give easy access to the terminals.

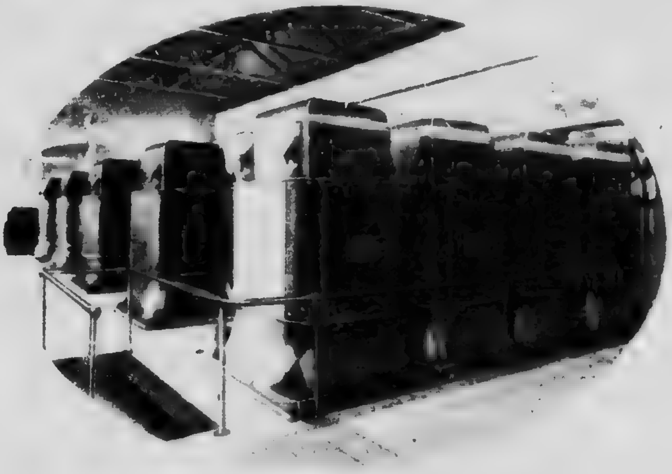


Fig. 948.—Group of Transformers Cooled by Air-blast

Air-blast Cooling.—This method consists in forcing cold air through carefully designed ducts provided between the coils and between sectionalised portions of the core. It is only applied to large transformers, and is not much used in this country.

A group of such transformers is shown in Fig. 948, the transformers being of a standard type manufactured by the General Electric Company, of Schenectady. The base of the transformer case is a cast-iron shell, and is placed directly over an air chamber supplied with air by a suitable blower usually driven by an electric motor. Part of the cold air passes vertically through the coils and out through the top of the transformer, whilst another part is diverted horizontally through ventilating ducts in the core, which is of the shell type, and passes off at one side of the transformer. Suitable dampers control the relative amounts of air passing through the core and the windings respectively. The amount of air required is about 150 cubic feet per minute at a pressure of $\frac{1}{2}$ to 1 ounce per square inch ($4\frac{1}{2}$ to 9 lbs. per square foot) for each kilowatt loss in the transformer.

Comparison of Methods.—The selection of the particular method of cooling to be adopted in a given case requires a careful consideration of all the circumstances. Each of the main types described above can be made equally reliable and efficient. For small installations the fact that they are self-contained and require no auxiliary apparatus leads usually to the adoption of air-cooled insulated transformers.

For large installations the water-cooled type is the least expensive for first cost, but the cost of supplying and maintaining a supply of water must be taken into account. If pumps are necessary the whole arrangement would probably be more expensive than with blowers. The air-blast installation requires the most space, but the transformers are less expensive than air-cooled insulated transformers of similar rating. As the transformers are open at the top they must not be placed where dirt or water from any source is liable to fall on them. They cannot also be designed for voltages much in excess of 35,000 or 40,000 volts, because of the great thickness of solid insulation required in the absence of insulating oil and the consequential difficulty in conducting the heat from the copper to the cooling air. On the other hand the other two types of transformers are available for all voltages which are within the limitations of transmission difficulties.

VIII. ELEMENTARY THEORY OF THE STATIC TRANSFORMER

In heavy electrical engineering work the main function of the static transformer is to change the energy of an alternating current or currents into similar energy at a different voltage. Incidentally, and for special purposes, the number of phases and the phase relations may also be changed and other functions of more or less importance may be compassed.

Voltage Ratio.—The general elementary theory of the change of voltage is simple, and may be given as follows. For simplicity, assume that the transformer is unloaded, that is, that there is no current in the secondary circuit. Since there is no alternating current flowing through the primary windings there will be an alternating magnetic flux in the iron which, in accordance with Faraday's law of electromagnetic induction (*see* p. 423, Vol. I.) will give rise to a back E.M.F. in the coils dependent at any instant on the rate of change of the flux. Now let:

N = the maximum value of the magnetic flux;

I_1 = R.M.S.* value of the primary current;

* The meaning of this and other terms is explained at page 760 and elsewhere in Vol. I.

E_1 and E_2 = the R.M.S. values of the primary and secondary E.M.F.S respectively;

S_1 and S_2 = the number of turns on the primary and secondary windings respectively;

n = the number of cycles per second, i.e. the periodicity;

A = a numerical coefficient, chiefly depending on the law of variation of the flux;

then on the assumption that there is *no magnetic leakage*, or, in other words, that the whole of the magnetic lines set up by the current in the primary pass through all the turns of the primary and of the secondary, we have:—

$$\left.\begin{aligned} E_1 &= A\,n\,S_1\,N \\ E_2 &= A\,n\,S_2\,N \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

since every turn of the primary and of the secondary will have impressed upon it at any instant the same E.M.F. and the items in each complete winding are in series. From these equations it follows that

$$\frac{E_1}{E_2} = \frac{A\,n\,S_1\,N}{A\,n\,S_2\,N} = \frac{S_1}{S_2} \quad . \quad . \quad . \quad (2)$$

The ratio k, which is the ratio of the number of turns in the two windings, and is therefore a constant, is known as the *ratio of transformation*. The reader should carefully note the condition under which it becomes the ratio of the two inductive E.M.F.S.

If we further assume that the voltage drop due to ohmic resistance in the primary winding is negligible, we have:—

$$\frac{V_1}{V_2} = \frac{E_1}{E_2} = k \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where V_1 is the voltage impressed on the primary terminals and V_2 is the voltage measured at the secondary terminals.

Effect of Resistance.—To allow for the ohmic drop in voltage, excluded above, let the secondary be loaded with a *non-inductive* external *resistance* R_2, and let

r_1 and r_2 = the resistances of the primary and secondary windings respectively;

e = the induced E.M.F. in *each* turn of the primary and secondary windings (still with *no magnetic leakage*);

then

$$\left.\begin{aligned} V_1 &= S_1\,e + r_1\,I_1 \\ 0 &= -S_2\,e + (r_2 + R_2)\,I_2 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (4)$$

hence by eliminating e we have:—

$$\left.\begin{aligned} S_2\,V_1 &= S_2\,r_1\,I_1 + S_1\,(r_2 + R_2)\,I_2 \\ \text{also} \qquad A_t &= S_1\,I_1 - S_2\,I_2 \end{aligned}\right\} \quad . \quad . \quad (5)$$

where A_t is the sum of the ampere-turns acting on the core of the transformer. From equations (5) we get by eliminating I_1:—

$$I_2\,[(S_2^2\,r_1 + S_1^2\,(r_2 + R_2)] = -S_1\,S_2\,V_1 + S_2\,r_1\,A_t$$

or
$$I_2 = -\frac{S_1\,S_2\,V_1}{S_2^2\,r_1 + S_1^2\,(r_2 + R_2)}\ \text{approximately};^*$$

whence
$$I_2 = -\frac{V_1\,\frac{S_2}{S_1}}{(r_2 + R_2) + r_1\left(\frac{S_2}{S_1}\right)^2},$$

and finally
$$I_2 = -\frac{\frac{V_1}{k}}{(r_2 + R_2) + \rho},\ \text{where}\ \rho = \frac{r_1}{k^2} \quad . \quad . \quad (6)$$

This approximate result is interesting and easily remembered. It is that the current in the secondary on a non-inductive load (R_2) is the current, at unit power factor, of a circuit in which the E.M.F. is the voltage impressed on the primary terminals altered by the ratio of transformation, and the resistance is the actual resistance increased by the resistance of the primary coil divided by k^2. Similarly, if we eliminate I_2 from equation (5) and again treat A_t as negligible, we find that:—

$$I_1 = \frac{V_1}{r_1 + (r_2 + R_2)\,\frac{S_1^2}{S_2^2}} \quad . \quad . \quad . \quad . \quad (7)$$

$$I_1 = \frac{V_1}{r_1 + (r_2 + R_2)\,k^2} \quad . \quad . \quad . \quad . \quad (8)$$

which shows that, neglecting the magnetising ampere-turns, the primary current is equal to the impressed voltage divided by the resistance of the primary coils increased by the resistance of the secondary circuit multiplied by k^2. The case where $R_2 = 0$, that is when the secondary is short-circuited, is of special importance. In this case

$$I_1 = \frac{V_1}{r_1 + r_2\,k^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and the added resistance is that of the secondary coils multiplied by k^2. It is curious to note that this added resistance (which makes the allowance for ohmic drop) is the resistance of a coil having the number of turns of the primary wound into the copper space occupied by the secondary; it is sometimes referred to as the *equivalent resistance* of the transformer. By comparing equations (6) and (8) it is obvious that, under the conditions set forth,

$$I_2 = -I_1\,k \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Magnetic Flux and Magnetising Current.—When, as is always the case in practice, there is magnetic leakage, the quantity e used in equations (4) is no longer the same for every complete turn in the primary, and still less in the secondary, winding. The equation

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* The quantity A_t is the magnetomotive force (M.M.F.) divided by $4\pi/10$ (= 1·26), and the M.M.F. = Hl where H is the magnetising force and l is the length of the magnetic circuit. Since the magnetic circuit is a good one with no non-magnetic gaps the value of Hl is very small, and A_t is therefore taken to be negligible.

$$v_1 = e_1 + r_1 i_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

in which v_1, e_1, and i_1 are the *instantaneous* values at any given moment of the R.M.S. quantities, V_1, E_1, and I_1 still holds good. From this it follows that if $r_1 i_1$ be negligible, which is practically true, v_1 and e_1 have the same wave-form. If this be a simple sine wave the *magnetic flux* also consists of a sine wave of flux, for it is on its rate of change that e_1 depends, and, as has been pointed out elsewhere, the curve whose *rate of change* is a sine curve is another sine curve displaced 90° or a quarter-period.

If we pass from the instantaneous equation (11) to the corresponding equation

$$V_1 = E_1 + r_1 I_1 \quad . \quad . \quad . \quad (12)$$

in which measured (*i.e.* R.M.S.) values of voltages and currents are used, then it must be remembered that this equation is a vector equation, and unless V_1 and I_1 are "in phase" the quantities on the right-hand side must be added vectorially (*see* Vol. I., pages 542 *et seq*), as in Fig. 949, which is a diagram for the primary circuit of an *unloaded* transformer. Here O V_1 and O I_0* are the vectors of the impressed voltage, and the current flowing, which lags by the angle V_1 O I_0 behind the voltage. To find the quantity E_1, the vector V_1 F_1, equal to $r_1 I_1$ in magnitude, must be drawn parallel to I_0 O, and the line O E_1 will be the required vector.

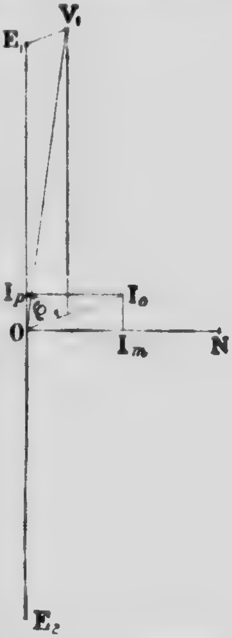

Fig. 949.—Vector Diagram of an Unloaded Transformer.

Magnetising Current.—Now if the flux were always strictly proportional to the magnetising current, as in a solenoid with an air core and field, the latter would also, in the case supposed, follow a sine law. But this simple result is interfered with by the fact that such a relation does not hold, and still further by the existence of hysteresis. Examples of the curves connecting magnetising force or, in the case of an iron-cored solenoid, magnetising current and magnetic flux, have been referred to frequently in the foregoing pages, and more especially in Vol. I. in the section on the "Magnetic Properties of Iron" on pages 286 to 300. They are curves which do not admit of easy mathematical expression, and therefore, in any application of them to a practical problem, recourse is generally had to graphic methods. In what follows such a method is used in solving the present problem.

In Fig. 950 a hysteresis loop B B B, such as might be expected to be true for a good modern transformer, is shown on the left. Since the circuit is practically without any non-magnetic gaps the sides of the loop are steep, and since good magnetic material is used the loop is in reality narrow, though for clearness in following the construction the magnetising current scale is taken large, so as to give a wide loop. The maximum flux density chosen is less than in generators, and some other electrical machinery (*see* Table IX., page 879). The transformer is assumed to be unloaded.

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* In what follows I_0 is the primary current in an unloaded transformer or, in other words, the *no-load* current.

On the right-hand side N N N is the sine wave of flux on the same zero line as B B B, and the method is to work backwards from N N N through B B B to discover the different values of the current, measured horizontally on the B B B curve, necessary to produce the various points in N N N. These values, plotted vertically, give the curve C C C, in which the vertical heights of the points are determined by the horizontal distances of the corresponding points on B B B from the axis Y Y. Thus c_2 on the rising curve of B B B corresponds to c_2 on the rising curve of C C C, and c'_2 on the falling curve of B B B corresponds to c'_2 on the falling curve of C C C, and so on for other points. The currents shown by the curve C C C will give the sine wave of flux B B B, which by its variation will produce a sine wave of E.M.F. directly opposed to the impressed voltage V V V.

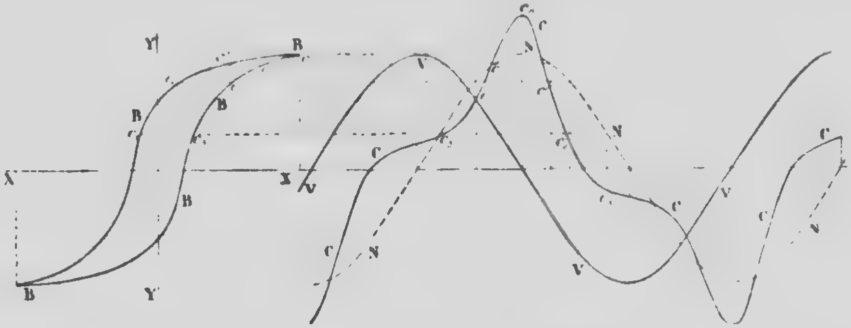

Fig. 950.—Curves of Impressed Voltage, Flux and Magnetising Currents.

The curve C C C is obviously not a simple sine curve, but contains harmonics (*see* page 782, Vol. I.) superposed on such a curve. Such harmonics, due, as we have said, to the shape of the magnetisation curve and hysteresis, increase the ohmic heat produced by the current in flowing through the primary coil.

Eddy Currents.—Another disturbing effect in an actual transformer is the existence of eddy currents in the iron, which absorb energy and act physically so as to produce a small back E.M.F. in the primary circuit approximately in opposite phase to the current.

Energy Losses: Unloaded Transformer.—The losses of an unloaded transformer, that is, a transformer with no secondary current, are not, therefore, confined to the $r_1 I_0^2$ losses due to ohmic resistance. The primary current has, in addition, to supply the energy lost in hysteresis and in eddy currents in the iron sheets, which are practically constant for a given magnetising current. As these losses are small in proportion to the energy dealt with by the loaded transformer, it is convenient to express them in the same way as the ohmic loss, namely as $w = R_0 I_0^2$, where w is the sum of the two "iron" losses and R_0 is a multiplier which enables us to express these losses as if they were due to ohmic resistance. The total losses are therefore

$$w_0 = (r_1 + R_0) I_0^2$$

and the multiplier $(r_1 + R_0)$ is to be used for the vector $V_1 E_1$ in Fig. 949 instead of the simpler multiplier r_1.

Even with this addition the size of $V_1 E_1$ in Fig. 949 has been exaggerated to obtain a well-defined figure.

Loaded Transformer without Magnetic Leakage. In the diagram in Fig. 949, which is the vector diagram of an unloaded transformer, $O I_0$ is the no-load current, and is nearly, but not quite, in quadrature with the induced voltage E_1. It may be conveniently regarded as consisting of two vectors I_m, the *magnetising* current which is necessarily at right angles to E_1 and *wattless*, and I_p, the *power* current in phase with E_1, and which supplies the energy lost through the existence of resistance, hysteresis and eddy currents. The E.M.F. in the open-circuited secondary coil will be $O E_2$ equal and opposite to $O E_1$.*

Let the secondary of the transformer be now loaded with a non-inductive load, which will require the primary current to be increased to supply the additional energy required by the secondary circuit. Assuming the flux to be maintained as before, it is evident that the net current available for magnetisation and hysteresis, etc., losses must still be $O I_0$, which must now be the resultant of the currents in both coils. We therefore first draw O N (Fig. 951) as before, to represent the flux, and vectors $O E_1$ and $O E_2$ equal and opposite to represent the E.M.F.s, it being assumed that there is *no magnetic leakage*; $O E_2$ represents the E.M.F. in the secondary coil, and $O E_1$ the portion of the impressed voltage which balances the equal E.M.F. in the primary coil. $O E_2$ necessarily lags 90° behind O N, whilst $O E_1$ leads by 90°.

Since the secondary circuit is non-inductive, the current is in phase with the E.M.F., and we may mark off along OE_2 a vector OI_2 to represent, on the current scale, the secondary current I_2. The primary load current OI_1 will be found by drawing the parallelogram $I_2 I_0 I_1 O$ so that OI_0 shall be the resultant of OI_2 and OI_1. The current OI_1 absorbs a certain voltage Or_1, equal to $r_1 I_1$ because of ohmic resistance, and OV_1, the impressed voltage required to supply both OE_1 and Or_1, is obtained by combining these vectors. OV_1 is therefore the potential difference at the primary terminals, and OV_2, the potential difference at the terminals of the secondary, is the difference between OE_2 and the internal drop E_2V_2, which is equal to r_2I_2 and is in phase with E_2. The general effect is that the voltage OV_1 in Fig. 951 appears a little greater than in Fig. 949, and OV_2 less than OE_2, the potential difference in the open-circuit case. The magnetising current has, however, been exaggerated as compared with the other currents in order to obtain a clearer diagram. In modern transformers it may be no larger than one-fiftieth of the full-load primary current.

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* Here, and in what follows the transformer, in order to simplify the diagrams, is assumed to be a "*1 to 1 transformer*" with $S_1 = S_2$, that is with $k = 1$. When the number of turns in the two coils is not the same, the ampere-turns instead of the amperes should be plotted whenever magnetising effects are being dealt with. In the perfect transformer where $E_1 I_1 = E_2 I_2$ we would also have $S_1 I_1 = S_2 I_2$ (*see* equation (2), page 929). *Alternatively* the diagrams may be constructed by using *different scales* for the two circuits; in this case the volt scale of the secondary will be the *volt scale* of the primary with all the scale numbers *divided* by k, and the ampere scale of the secondary will be the *ampere scale* of the primary with all the numbers *multiplied* by k.

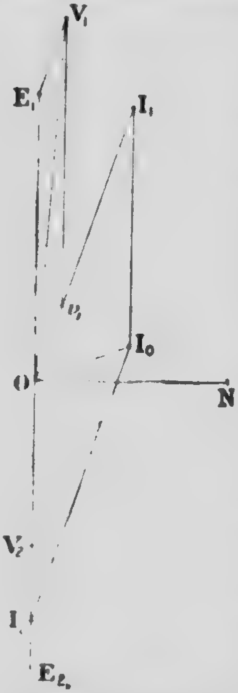

Fig. 951.—Vector Diagram of Loaded Transformer (no magnetic leakage).

Magnetic Leakage.—There is in addition, however, in modern transformers some magnetic leakage which means, as in the case of induction motors (*see* pages 768 to 774), that all the lines set up by the primary current do not link through the secondary windings and *vice versa* as regards the magnetic effect of the secondary current. The result is that the flux through the primary is greater than the flux N through the secondary, and therefore OE_2 in Figs. 949 and 951 should be diminished. In the secondary, when under load, there is also a leakage field which does not pass through the primary windings, and therefore has to be supplied by the secondary current. It will be convenient to designate the common flux by N and the *leakage* fluxes by N_1 and N_2 respectively, all these symbols denoting maximum values.

We are now ready to deal with the "voltage drop" of a transformer having magnetic leakage and loaded with a non-inductive load. The action as regards the common flux N follows the same lines as in Fig. 951, but the leakage fluxes N_1 and N_2 are now superposed each for its own circuit. The easiest way of dealing with these is to regard their effects as voltage reactances ($= pLI$) vectorially at right angles to the currents producing them, these reactances being added to a transformer having no magnetic leakage in which the flux is N. As in the previous case, it will be best to commence with the secondary side and work backwards to the primary terminals.

Let O E_2 (Fig. 952) be the E.M.F. in the secondary due to the flux O N, there being an equal E.M.F. in the primary balanced by the voltage O E_1, which is one of the components of the voltage applied at the primary terminals. If O e'_2* be the magnitude of the voltage reactance $p L_1 I_2$ due to the leakage flux N_2, its vector direction can be ascertained by marking off on the semicircle $E_2 V'_2$ O the chord $E_2 V'_2 = O e'_2$ and drawing O e'_2 parallel to that chord. O V'_2 will then be the part of the E.M.F. O E_2 used against resistance, and $V'_2 E_2$ the part balancing the reactance. The voltage at the secondary terminals will be O V_2, which is less than O V'_2 by $V'_2 V$, the voltage required to drive the current I_2 through the resistance of the secondary of the transformer.

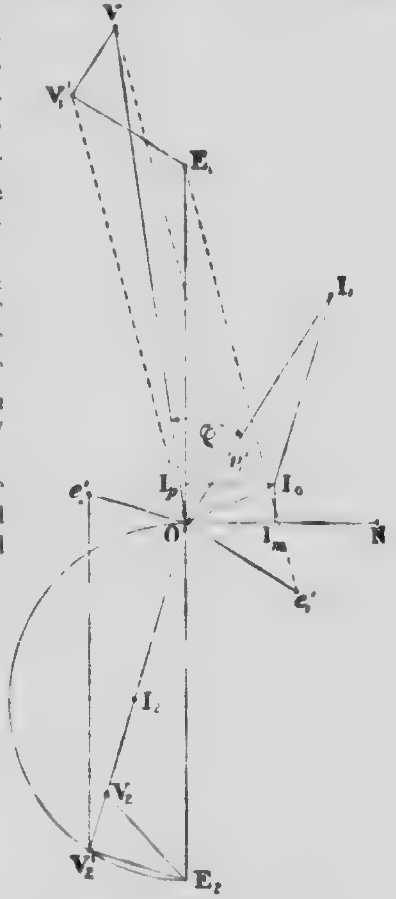

Fig. 952.—Vector Diagram of Loaded Transformer (with magnetic leakage)

The current in the secondary will be in phase with O V_2 and may be represented on the current scale by O I_2. Combined with the current in the primary, it gives the currents I_m and I_p (*see* also Fig. 949), which are the magnetising and the working currents of the no-load current O I_0. The primary current O I_1 can be found from O I_2 and O I_0 by the usual parallelogram construction, and the reactance voltage O $e'_1 = p L_1 I'_1$ in the primary coil is at right angles to O I_1. In addition to the voltage e'_1 O required to balance the reactance voltage, the impressed voltage at the terminals must also supply the voltage O v'_1 (rather greater than $V'_2 V_2$ because of the greater current) required to drive the current O I_1 through the resistance of the primary coil. These voltages

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* If the leakage fluxes N_1 and N_2 are known, the values of e'_1 and e'_2 can be calculated from the equations:—

$$e'_1 = 4{\cdot}44\, n\, S_1 I_1 N_1 \div 10^8 = I_1 X_1$$
$$e'_2 = 4{\cdot}44\, n\, S_2 I_2 N_2 \div 10^8 = I_2 X_2$$

the quantities X_1 and X_2 being the reactances, $p L_1 I_1$ and $p L_2 I_2$.

$E_1 V'_1$ (= $c'_1 O$) and $V'_1 V_1$ (= $O v'_1$) being added to $O E_1$ by the usual constructions, we obtain the voltage $O V_1$, which must be impressed on the primary terminals to obtain the required voltage $O V_2$ at the secondary terminals. From the method of construction it is obvious that $O V_1$ is greater than $O E_1$, and since $O E_2$ (= $O E_1$) is greater than $O V_2$ it follows that $O V_1$ is greater than $O V_2$. The difference between the two, often expressed as a percentage, is the *voltage drop* of the transformer.

The case of an inductive load being placed on the secondary terminals is left as an exercise to the student. By following the construction of Fig. 952 he can solve any given case by allowing for the inductance of the whole circuit in drawing $E_2 V'_2$ and remembering that $O V_2$ and $O I_2$ are no longer in phase.

Power Factor.—The phase relations are given by the diagram in Fig. 952, and are interesting. Thus the angle $V_1 O I_1$ is the angle of lag (ϕ) of the primary current behind the impressed voltage and the cosine of this angle is the power factor.

The currents $O I_1$ and $O I_2$ are not exactly in opposite phases, but it has been already explained that the magnitude of the magnetising current, and consequently of all quantities dependent on it, has been exaggerated so as to obtain a clear diagram. In modern transformers the losses are proportionately much less than is assumed in these diagrams, and consequently the primary and secondary currents are much more nearly in directly opposite phases.

Equivalent Coils.—The effect of the voltage $O V_1$ and current $O I_1$ at the primary terminals is to produce a certain voltage $O V_2$ and current $O I_2$ at the secondary terminals, the voltage drop being due to ohmic resistances and inductive reactances in both the primary and the secondary circuits. There is, in addition, the change of voltage due to the relative number of turns on the primary and the secondary, that is, to the *ratio of transformation k.* A *perfect transformer* may be imagined which has neither resistance nor inductive drop, and which would therefore give at the secondary terminals for all loads the voltage of the primary divided by k, but in directly opposite phase. Such a transformer would have an efficiency of 100 per cent.

It is convenient in practice to compare an actual transformer with the corresponding perfect transformer. The most important differences are the lowered efficiency and the lowered voltage at the secondary terminals, the latter being usually referred to as the "voltage drop," the scales being adjusted for the ratio of transformation as already indicated (see page 933, *footnote*), and the drop being, as a rule, expressed as a percentage of the actual pressure. The lowered efficiency is due to the energy losses in the transformer, these consisting of "iron" losses caused by hysteresis and eddy currents in the iron, and "copper" losses due to the ohmic resistance of the copper circuits. Modern transformers are designed so that these two classes of losses shall be practically equal at full load. Thus, if the total loss is 4 per cent. at full load, 2 per cent. should be made up of "iron" losses and 2 per cent. of "copper" losses. The first-named are practically constant at all loads; the second depend on the resistances and the squares of the currents, and therefore vary with the load.

The actual transformer therefore differs from the perfect transformer by having inductance and ohmic resistance in its copper circuits, and by the "iron" losses. There is also the wattless magnetising current, which by itself would cause a slight phase displacement without lowering the efficiency. For instance, if we re-draw (Fig. 953) the vectors $O V_1$ and $O V_2$ of Fig. 952, reversing the latter because of the change of direction, we see that the actual voltage drop is represented by the vector $V_1 V_2$. This drop can be resolved in many ways into a combined ohmic and inductance drop by describing a semicircle on $V_1 V_2$ and drawing lines from V_1 and V_2 to points on it. Two cases only, however, need be considered—one in which $V_2 P'$, in phase with I_2, is the ohmic and $V_1 P'$, at right angles, is the inductive drop, and the other in which $V_2 P$, in phase with I_1, is the ohmic and $V_1 P$, at right angles to it, is the inductive drop. The great difference between these two cases is due to the large value assumed for the no-load current I_0 in Fig. 952. With a value nearer to what obtains in practice P would be much closer to P′.

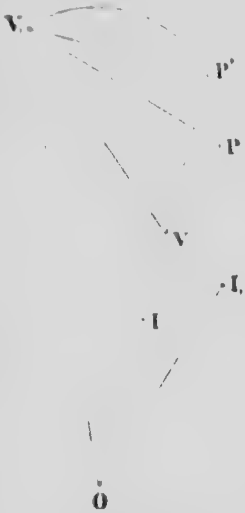

Fig. 953.—Vector Diagram for Inductive Drop

If the input current I_1 is taken as the multiplier, a coil with a reactance $p L$, such that $p L I_1 = V_1 P$ (Fig. 953), and a resistance R, such that $R I_1 = V_2 P_1$, would be a coil "equivalent" to the transformer. If, on the other hand, I_2 be the multiplier, we must have L and R, such that $p L I_2 = V_1 P'$ and $R I_2 = V_2 P'$. As in practice P and P′ are close together, there is but little difference, and I_1, the input current, and the point P are usually adopted.

To deal with this problem, Dr. Kapp introduces two other theoretical coils, which are supposed to be placed as *shunts* across the supply mains, and whose electrical constants are an inductionless resistance R_0 such that $R_0 I_0^2$ is equal to the no-load loss, and a resistanceless inductance L_0, such that $p L_0$, the reactance when multiplied by I_m, the magnetising current, is equal to V_1, the full line voltage used in making the no-load test. The no-load current I_0 and power w are obtained by tests at full working voltage, the secondary being open-circuited, that is, unloaded. Reference is made to the details of such a test later. If I_0 and w be the current and power so measured, and V_1 the working voltage, OE_1 and OV_1 (Fig. 949) are very nearly in phase and the angle (ϕ) of lag V_1OI_0 is given by

$$\cos\phi = \frac{w}{V_1 I_0}$$

The wattless component of the current I_0 is

$$I_w = I_0 \sin\phi$$

the working component being

$$I_p = I_0 \cos\phi = \frac{w}{V_1}$$

By far the greater part of the last-named component is due to the iron losses, the value of $r_1^2 I_0$, the copper losses, being so small as to be quite negligible.

These coils, combined with a *series* coil having constants L and R, such that

$$pL = \frac{\text{inductive drop}}{I_1}$$

$$R = \frac{\text{ohmic drop}}{I_1}$$

will then be "equivalent" electrically to the actual transformer. The advantage of using shunt coils for the "iron" losses of the transformer is that they leave the pass on voltage unchanged to the equivalent series coil, having an equivalent resistance R and an equivalent reactance pL.

The value of R, the "equivalent" resistance, has already been worked out above, for it is independent of magnetic leakage. It is (*see* page 930)

$$R = r_1 + r_2 k^2 \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Similarly, if pL_1 and pL_2 be the separate reactances of the primary and secondary circuits due to magnetic leakage, the "equivalent" reactance can be shown to be

$$pL = pL_1 + pL_2 k^2 \quad . \quad . \quad . \quad . \quad (14)$$

or

$$= X_1 + X_2 k^2$$

where X_1 and X_2 can be calculated as explained on page 935 (*footnote*).

Predetermination of the No-load Current.—An approximate value of I_w, the magnetising current, can be readily calculated from the details of the magnetic circuit, which, it will be remembered, consists in ordinary transformers almost entirely of magnetic material, which for the purposes of this calculation we may assume to be of uniform cross-sectional area (A) throughout the length (l) of the median line of the flux. The fundamental equation of the magnetic circuit (*see* page 283, Vol. I.) may be written

$$N = \frac{\frac{4\pi}{10} n_1 (I_w \sqrt{2})}{\frac{l}{\mu A}}$$

from which, remembering that $N = \mathbf{B}A$, we can at once deduce

$$I_m = \frac{\mathbf{B}l}{\sqrt{2}\cdot\frac{4\pi}{10}\mu s_1} = \frac{0\cdot505\,\mathbf{B}l}{\mu s_1}.$$

The value of I_p, the other component of I, can be calculated from the equation $w = V_1 I_p$ if the loss w allowed in the iron is known.

The magnitude of the no-load current is then determined from the equation

$$I = \sqrt{I^2_m + I^2_p}$$

Short-circuit Test.—The most convenient method of obtaining the "inductive drop" is by the short-circuit test, which consists in short-circuiting the secondary and applying such a voltage to the primary as will generate the full-load current in the secondary. The practical details of this test are given later.

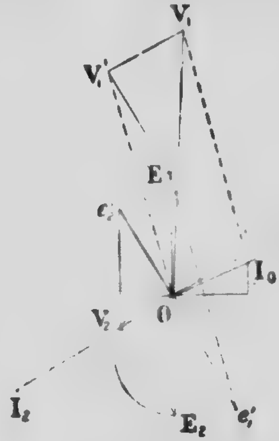

Fig. 954.

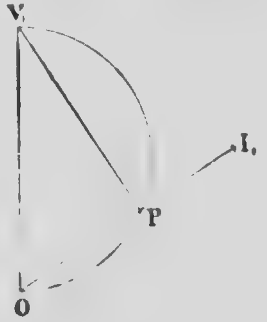

Fig. 955.

Vector Diagrams of Short-circuited Transformer and its Inductive Drop.

The vector diagram of the test is given in Fig. 954, which is Fig. 952 modified by making OV_2 equal to zero, whilst OI_2 is unchanged in magnitude. The same letters are used for similar points in the two figures, and the only discrepancy is that I_0, for obvious reasons, has not been reduced sufficiently. The student should compare the construction of Fig. 954 with that of Fig. 952. The result is that to obtain the E.M.F. OE_2 in the secondary coil, with no voltage on the terminals, the applied voltage must be OV_1. This quantity OV_1 is therefore the inductive drop, since it is all used up in the transformer. It is set out separately in Fig. 955, which is a diagram corresponding to Fig. 954, the same scales being used. It is interesting to note that OV_1, in Fig. 955, is practically equal to V_2V_1 in Fig. 953, though the phase angle is different. The inductive components $p \mathrm{L} \mathrm{I}_1$ of the drop is $\mathrm{V}_1 \mathrm{P}$, and the resistance component $\mathrm{R} \mathrm{I}_1$ is O P. As the current I and the voltage $\mathrm{O} \mathrm{V}_1$ are measured, and R is known from equation (11) it is obviously possible to find the "equivalent" reactance $p \mathrm{L}$.

The application of vector diagrams to transformer working as exemplified above has been much further elaborated. Considerations of space prevent us from dealing with the theory in greater detail.

IX.—STATIC TRANSFORMER WORKING

As a static transformer has no moving parts, its operation in practice is quite a simple matter compared with that of moving machinery. The problems which arise are chiefly concerned with the arrangement and switching of the circuits to secure the desired transformation and the protection of the apparatus from dangers which may be expected to arise.

Transformations required in Practice. The main transformation usually, but not always required, is a change of electric pressure or voltage, with or without change of phase. Change of periodicity may also be demanded.

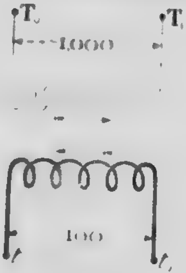

Fig. 956.

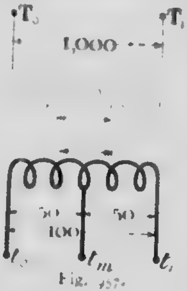

Fig. 957.

Single-phase Transformer Connections.

Diagrams of Connections.—The representation of the electric circuits of a static transformer diagrammatically is simple, but to make matters quite clear it is desirable to combine it with a brief summary of the above transformations other than the "stepping-up" or "stepping-down" of the voltage.

These transformations may conveniently be diagrammatically represented as in the following figures, there being no tappings, usually so-called, or auxiliary apparatus shown. The marking of the terminals is in accordance, so far as possible, with standard practice, and the relative voltages, when of interest, are given by the numbers inserted.

Single-phase to Single-phase.—This with (*a*) two terminals for each circuit scarcely requires any diagram, but for completeness one is given in Fig. 956. If, however, the secondary, as is sometimes required, is (*b*) to supply a three-wire network, the diagram will be as in Fig. 957. The terminal for the middle wire is marked t_m.

Two-phase to Two-phase.—Here two cases arise. In both the primary are supposed to be the high-voltage circuits, and to require four terminals and four supply wires. In one case (Fig. 958) the low-voltage circuits are similar, and consist of two independent circuits with the currents in quadrature, starting each from two terminals on the transformer. In the other (Fig. 959) the secondary circuits supply a three-wire system, the currents on the two sides being in quadrature, but differing from those Fig. 958 by the voltage across the outers being available for working at a voltage 1·41 (= $\sqrt{2}$), the voltage of either side.

The vector diagram (*see* page 766) for Fig. 959 is given in Fig. 960, the potential difference of the terminals $a_0 a_1$ being represented by the vector Y O and that of the terminals $b_0 b_1$ by the vector O X. The resultant vector Y X represents the potential difference of the terminals $a_0 b_1$.

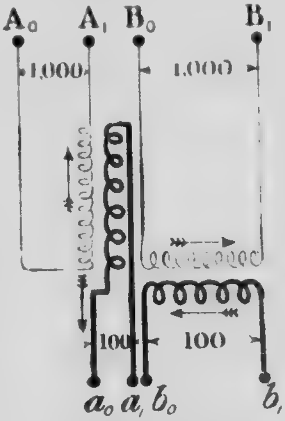

Fig. 958.—Two-phase Transformer Connections.

Three-phase to Three-phase. As we have shown elsewhere, this transformation can be effected either by a single transformer with six coils, three primary and three secondary, or by the joining-up of three similar single-phase transformers. The three coils on either side may be connected up either in "mesh" or in "star," and therefore four possible combinations arise, namely (*a*) "*mesh-mesh*," (*b*) "*mesh-star*," (*c*) "*star-mesh*," and (*d*) "*star-star*." The voltage relations are interesting, and are best illustrated by actual numbers. In the following diagrams we have assumed (i.) that the high-voltage side is the primary and is supplied with currents at 1,000 volts *between lines*, and (ii.) that the step-down ratio between coils on the transformer is 10 to 1. We have also (iii.) marked the corresponding coils A, B, C and *a*, *b*, *c* on the two sides and the coil terminals as before, the line terminals being marked X, Y, Z and *x*, *y*, *z* respectively. The figures given are for perfect transformers without any losses.

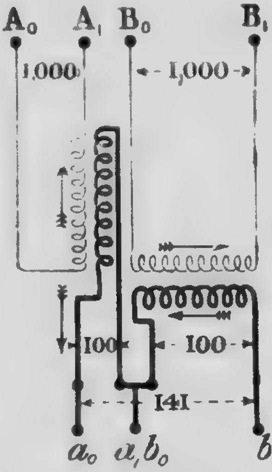

Fig. 959.

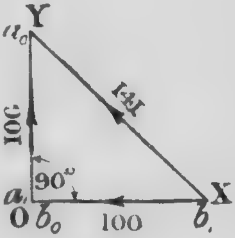

Fig. 960.

Two-phase Three-wire Load Connections.

Case (*a*)—the "*mesh-mesh*" connections is the simplest, as (Fig. 961) the primary coils A, B, C each receive the full line voltage of 1,000 volts, and the secondary coils *a*, *b*, *c* deliver to the lines *x*, *y*, *z* the simple transformed voltage of 100 volts.

Case (*d*)—the "*star-star*" connections—is equally simple, the line voltages (Fig. 962) between the secondary terminals being the line voltages between the primary terminals altered only by the ratio of transformation. Special notice should be taken of the difference in the voltages between the lines (1,000 and 100 respectively) and the voltages in the coils (577 and 58 respectively). This difference is fully explained in the next paragraph.

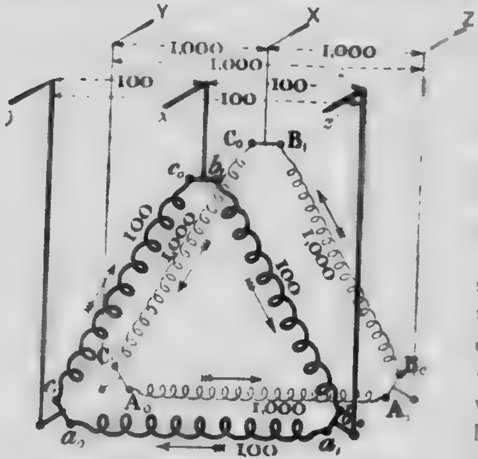

Fig. 961.—Three-phase "Mesh-mesh" Connections.

The other two cases are not so simple, since the coils across the lines are differently connected on the two sides. In the "*mesh-star*" case (*b*) (Fig. 963) the high-voltage (primary) coils are each bridged across the corresponding phase of the supply lines to receive the full line voltage of 1,000 volts. On the low-voltage (secondary) side, however, coils, each carrying a transformed voltage of 100 volts, are in series in pairs across the outgoing line. The 100 volts in each of any pair are, however, not in phase, the phase difference, owing to the method of connection, being 60° (180° – 120°). The voltage across any pair of terminals, e.g. *x y* (= $a_0 b_0$) is

$$2 \times \left(100 . \cos \frac{60^\circ}{2}\right) = 2 \times 100 \times \frac{\sqrt{3}}{2}$$

$$= 173 \text{ volts.}$$

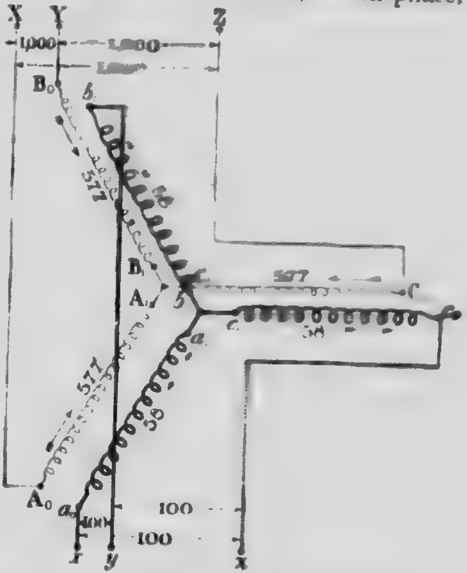

Fig. 962.—Three-phase "Star-star" Transformer Connections.

The voltage on the secondary lines is thus $\sqrt{3}$ times the transformed voltage of 100 volts.

In case (*c*) the position is reversed, for (Fig. 964) it is the primary coils which are in series across the supply lines, and therefore with 1,000 volts between, X Y (= $A_0 B_0$) only receives a pressure of

$$\frac{1000}{\sqrt{3}} = 577 \text{ volts.}$$

Thus the voltage in each of the secondary coils is only $\frac{577}{10} = 58$ volts, and, as these coils are bridged across the outgoing lines x, y, and z, this must also be the outgoing line voltage.

It will be noted that with a constant supply voltage of 1,000 volts three distinct voltages can be obtained on the secondary lines according to the method of connection adopted. These are 58, 100, and 173 volts respectively, the numbers being in the ratio of 1 : √3 : 3.

In the last case, the "star-star" case already referred to (Fig. 962), the pulling-down of the voltage per coil on the primary side is compensated by its being built up again on the secondary side, so that the line voltages to the two sides have the transformer ratio of 10 to 1.

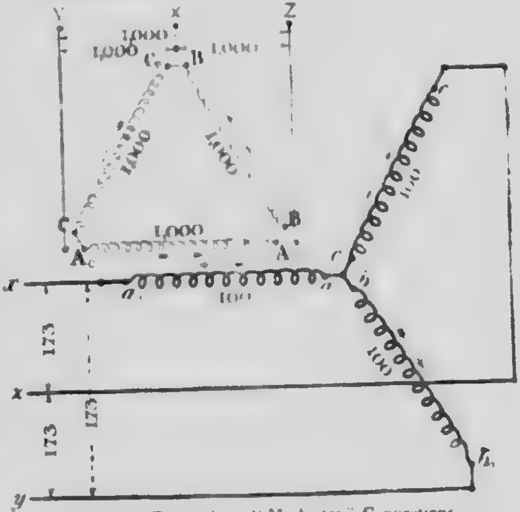

Fig. 963.—Three-phase "Mesh-star" Connections.

On each star diagram there is a common or neutral point N, which can be connected to a fourth terminal on its own side if so desired. The use of this terminal, as well as the reasons for adopting one or other of these four methods of connection, is referred to elsewhere.

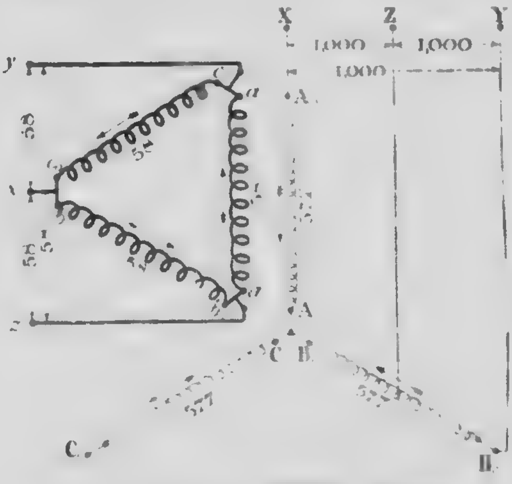

Fig. 964.—Three-phase "Star-mesh" Transformer Connections.

Star-zigzag.—Besides the above, which may be called the standard connections for three-phase to three-phase transformation there is a much less widely known method to which reference has already been made (*see* page 874) the "star-zigzag" method. It is useful in cases in which, the secondary being in "star," a variable part of the load may be joined up between line and neutral. In the case cited it was desired to place power loads at 400 volts three phase between lines, and lighting loads at 230 volts single phase between line and neutral on a public distribution network. It is obvious that in such a case the loads between line and neutral may at times be very much "out of balance," and in that event, should the high-voltage coils be also "star" connected, the system becomes unstable, and severe unbalancing of the voltages results. It is therefore usual to specify for such cases the "mesh-star" connection, which necessitates on the high-voltage side a more costly winding, especially on small transformers, than the cheaper "star" winding.

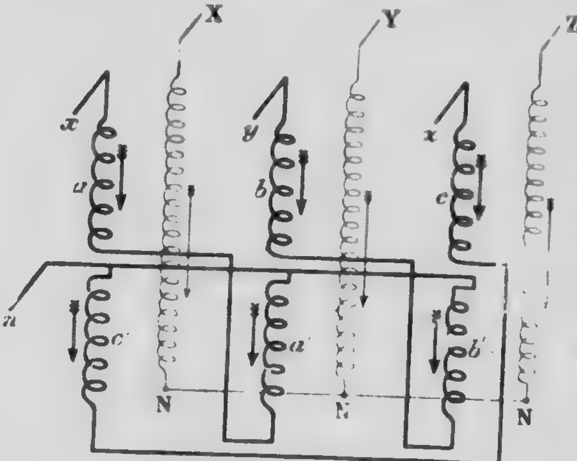

Fig. 965.—Three-phase "Star-zigzag" Transformer Connections.

These "star-zigzag" connections are shown quite simply in the diagram in Fig. 965. Both sides are "star" connected, but on the low-voltage side half the winding of each phase is on one limb, and the other half on the next limb with the connections reversed. Thus, for the "*x*" line half the winding *a* is on the X *x* limb, and the other half *a′* is on the Y *y* limb. The vector diagram of the low-voltage side is given in Fig. 966. For each phase the vectors of the half-coils are represented by dotted lines with a phase difference of 60°, and their resultant by a continuous line. This resultant voltage leads 30° on the limb voltage; for instance, the *x* voltage leads 30° on the *a* voltage, a point which must not be overlooked if it should be desired to parallel with ordinary "star"-connected secondaries. Another point is that the coils *a* and *a′* must be wound for a voltage of 132 volts if the resultant is to be 230 volts. This means that about 15 per cent. more copper must be used, and the secondary winding is more costly as well as more complicated. The extra cost, however, is much more than saved

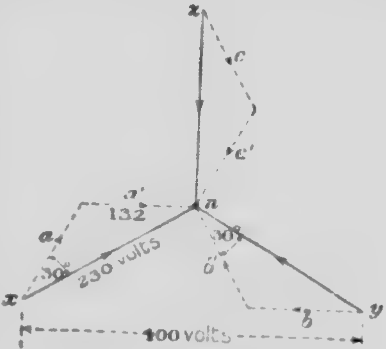

Fig. 966.—Vector Diagram of "Zigzag Connections.

on the "star" primary high-voltage winding. Moreover, an unbalanced load from lines to neutral does not render the primary unstable, because the want of balance is distributed on the limbs.

Line and Coil Phase Relations. Of even more importance than the voltage ratio of the supply lines and the coils of the transformer is their phase relation, especially when questions of parallel running have to be considered. The cases of most practical importance, and the only ones with which it is intended to deal here, are those of the "three phase to three-phase" transformation.

Take the "mesh" connections first, and, in Fig. 967, let the three sides of the equilateral triangle represent vectorially, as marked by the arrow heads A, B and C, the currents and the effective voltages, unit power factor being assumed, in the three coils $A_0 A_1$, $B_0 B_1$, and $C_0 C_1$, which are "mesh" connected. These currents are derived from the supply lines X, Y and Z, the currents in which are drawn in their correct angular positions relatively to the vectors of the currents in the coils of the mesh. The vector direction of these line currents is also marked by arrow-heads.

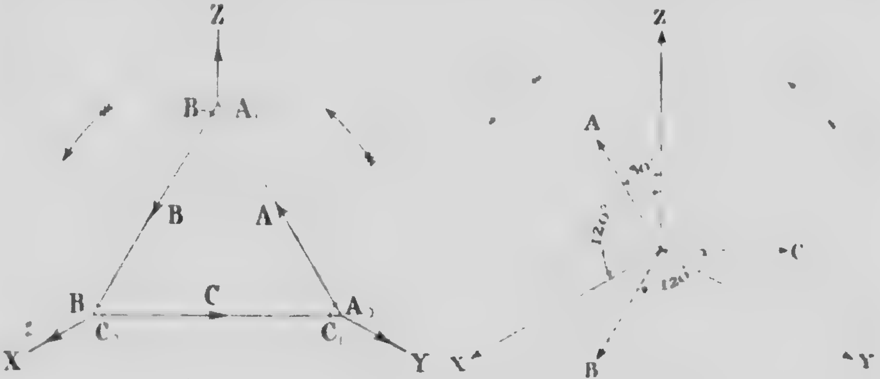

Fig. 967

Fig.

Vector Diagrams of "Mesh" Connections.

The clock diagram from which (see pages 540 to 548, Vol. I.) the six curves in their proper relative positions could be projected is given in Fig. 968. The radiating lines in this diagram are marked with the same letters as the vectors in Fig. 967, and are drawn parallel to these vectors, following the usual convention that the directions are all outwards from the central point. The lines are also of the proper relative lengths, representing the magnitudes of the currents, and it will be noticed that X, Y and Z are longer than A, B and C. The ratio is $\sqrt{3}$: 1, or 1·73 : 1.

The accuracy of this ratio can be proved by considering the relations of the currents at one of the points of the mesh triangle, for instance the X B C point. These vectors are re-drawn in Fig. 969, from which at first

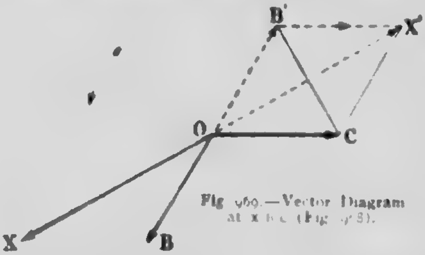

Fig. 969.—Vector Diagram at x b c (Fig. 968).

sight it would appear that these three vectors cannot possibly balance one another. A reference, however, to Fig. 967, which is a diagram of connections as well as a vector diagram, shows that at the point considered one of the vectors B is directed towards the point and the other two away from it, and therefore a current at that point will be *emergent* from B, giving *entrant* currents to X and C. In fact, in dealing with multipoint diagrams, such as Fig. 961, it must be remembered that a current-carrying conductor or coil has two ends, at one of which the current enters and emerges at the other. Now an emergent end evidently has, relatively to an entrant end, the opposite properties, which are conveniently designated by the signs + and —, or by the vector quantity concerned being regarded as 180° out of phase at the two ends, though it is, in fact, the same quantity.* If we agree that, at the junction under consideration, an emergent end shall conventionally be regarded as + (as in continuous-current generator working), then when we are combining the vectors X, B, C, we must regard X and C as — and B as +. If therefore we reverse B and draw it as B′ all the vectors will be — and the lines X, B′, and C give the correct phase relations and can be combined according to the usual rules. Combining B′ and C, we get in magnitude and direction the vector X′ equal and opposite to X, which it balances, fulfilling the usual condition. For magnitude the two triangles O B′ C and X′ B′ C are obviously equilateral, and

$$OX' = 2.OC. \cos 30° = 2.OC \times \frac{\sqrt{3}}{2} = \sqrt{3}\,OC.$$

Thus the ratio of the vector X to the vector C is √3 to 1.

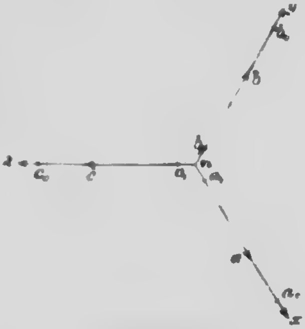

Fig. 970.—Vector Diagram of "Star" Connections.

Take next the case of "star" connections, as shown in Fig. 970, in which the phases of the currents are represented by the lines *x*, *y* and *z*, radiating 120° apart from the neutral point *n*, the directions of the vectors being again given by the arrow-heads. Distributing lines may be assumed to be attached to the points *x*, *y* and *z*, and the E.M.F.s giving rise to the currents may be assumed to be in the coils $a_1 a_0$, $b_1 b_0$, and $c_1 c_0$, and to be respectively derived from the fluctuations of the currents in $A_0 A_1$, $B_0 B_1$, and $C_0 C_1$ in Fig. 967. In practice this would make Fig. 970 the vector diagram for the currents, at unit power factor, in the star-connected secondaries of a transformer with a balanced load, the primaries of which are mesh connected, with the line currents and coil currents represented by the vectors of Fig. 967.

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* The author is, of course, aware that it is not the usual practice in alternating-current problems to regard a current at one end of a conductor or coil as in the opposite phase to the same current at the other end, but he contends that the convention—for it is only a convention—is convenient, and leads to clearness in drawing vector diagrams; in fact some such convention is always used, e.g. regarding one end of the coil as the beginning (*b*) and the other as the end (*e*), and treating these as symbols, with + and — significations.

The phases of the currents proceeding from the terminals *x*, *y* and *z* (Fig. 970), as compared with the phases of the supply lines X, Y and Z in Fig. 967, are both interesting and important. Following the usual cyclical rules, the coil in the mesh opposite the point at which the line X enters the mesh was marked A, and the phase of the current in this coil was in lagging quadrature with the phase of the current in X. In Fig. 967 the coil *a* carries a current in the opposite phase to that in coil A, and therefore the current in the line *x*, which is in phase with the current in coil *a* is in leading quadrature with the current in line X.

Paralleling Transformers. The above gives rise to very important results if it be required to run *three-phase transformers* (or banks of single-phase transformers connected for three-phase working) in parallel. No difficulty arises with voltages or phases on balanced loads if the transformers are wound for the same transformation ratio, provided the connections of the various transformers (or banks) are either "mesh-mesh" or "star-star." If, however, some of the transformers (or banks) are "mesh-star" or "star-mesh" connected, then, as seen in Figs. 963 and 964 (page 943), the windings will have to be adjusted to a different voltage ratio of transformation if the voltages on the outgoing secondaries are to have the same voltages as the "mesh-mesh" or "star-star" combinations. But even then it will not be possible to bunch all the *x* secondary terminals to form the outgoing *x* line of the paralleled transformers, because the phases of the "mesh-star" connected transformers will not correspond with the phases of the "mesh-mesh" and "star-star" connected transformers. It is, of course, a matter of labelling, as to which should be called the *x* lines on the secondary side; but whatever method be adopted for a "mesh-star" or "star-mesh" bank of transformers there can be no line in phase with the *x* line of a "mesh-mesh" or "star-star" bank. The phases must be wrong by either 90°, 210° (90° + 120°) or 330° (90° + 240°), and therefore if an attempt be made to run in parallel banks of transformers, differing so much in phase, there must be heavy circulating currents in the secondaries of the transformers, which, reacting inductively on the primaries, will throw the whole system out of gear.

It is obvious that even when the connections are such as to allow paralleling, and when also the voltages are all right, care must be taken,

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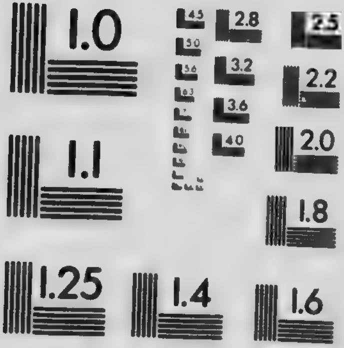

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as in the case of paralleling alternators (*see* page 396), that the phases on the transformers to be paralleled follow one another in the same and not in the opposite cyclical order. Methods of synchronising have been already described very fully (*see* Chapter III.) for alternators. The case of transformers is simpler, as the primaries are all connected to the same supply, and any change of phase in the supply lines alters all secondary phases equally. The subject is again referred to in greater detail in the chapter on sub-stations (*see* page 1245).

Phase Changing. Besides changing the voltage without changing the phase it is possible with static transformers to change simultaneously the voltage and the phase. The chief cases which occur in practice are :—

(i.) Two-phase to three-phase.
(ii.) Three-phase to six-phase.
(iii.) Single-phase to three-phase.
(iv.) Phase advancers.

The methods employed are, as a rule, reversible, and may be used for the contrary change.

Two-phase to Three-phase. The usual method of making this change is one suggested some years ago by Mr. C. F. Scott, of the Westinghouse Company. Two single-phase transformers have their primary circuits supplied with two-phase currents, that is, with voltages differing in phase by 90 electrical degrees; in other words, the currents in these circuits, on balanced loads and with unit power factor, are in quadrature, and the voltages are usually equal, e.g. 1,000 volts (R.M.S.) each. So far as the primaries are concerned the circuits are distinct, and are not interconnected in any way. The voltages of the secondaries, however, are not equal, one being 86·7 per cent. of the other. These secondaries are connected as shown in Fig. 971, in which X Y and Z W are the primary supply lines feeding the coils $A_0 A_1$ and $B_0 B_1$ respectively, with 1,000-volt currents. The coils have been set diagrammatically at right angles to indicate the phase difference. The secondaries are the coils $a_0 a_1$ and $b_0 b_1$, also set at right angles, but with the end b_0 joined to the middle of the coil $a_0 a_1$ at the point marked $a_{\frac{1}{2}}$; the line terminals are at a_0, a_1 and b_1, connected to the three-phase load lines x, y and z respectively. The voltage of the coil $a_0 a_1$ is taken to be 100 volts, in which case that of $b_0 b_1$ must be 86·7 volts. The direction vectorially of the E.M.F.s in the coils is indicated by the arrows.

The combination will give three-phase load currents in the lines x, y and z at a line voltage of 100 volts per phase. The vector diagrams showing how this result is attained are given in Fig. 972, in which the coils are marked as in Fig. 971. The phases of currents and voltages are shown by the arrows; in $a_1 a_0$ there is the 100 volts of the secondary of the leading phase $A_0 A_1$; in $a_0 b_1$ the half coil $a_0 a_{\frac{1}{2}}$ is combined with the secondary $b_0 b_1$ of the lagging phase $B_0 B_1$, giving a voltage whose vector is represented in magnitude and direction by the line $a_0 b_1$, which is one of the sides of the equilateral triangle $a_0 b_1 a_1$; finally, for the third phase, the coil $b_1 b_0$ is combined with the coil $a_1 a_1$, giving a voltage of 100 volts represented by the vector $b_1 a_1$.

In practice, similar transformers are used with their secondaries, provided with three tappings, namely the 50 per cent. tap in the middle, and two other tappings symmetrically disposed, that is 6·65 per cent. from each end, and therefore with a voltage between them of 86·7 per cent. of the full voltage. Thus either of the transformers can be used in either of the positions of Fig. 971.

Three-phase to Six-phase. In modern working this transformation is exclusively required for supplying current to six-phase rotary converters, and it will be more convenient to deal with in connection with the control and working of such converters (*see* pages 986 to 993).

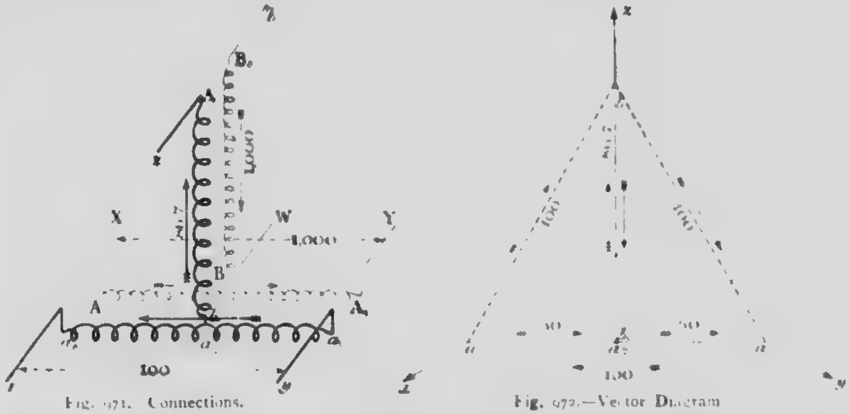

Fig. 971. Connections. Fig. 972.—Vector Diagram

Two-phase to Three-phase Transformation (Mr. Scott's method)

Single-phase to Three-phase.—This transformation cannot be obtained by the use of static transformers only, but requires the assistance of an induction motor. It might, therefore, have been as appropriately described in the section dealing with such motors, but it is more convenient to take it here.

The diagram in Fig. 973 shows the connections for a single-phase high-voltage line supplying current to a low-voltage three-phase traction motor. The method is not new, but it has recently been applied on an engineering scale on the main line of the Norfolk and Western Railway in Virginia, the diagram being taken from an article on this railway in the *Electric Railway Journal.* The voltages given are those used in this instance.

The voltage on the primary of the single-phase transformer is 11,000 volts, and the windings are such as to generate 750 volts on the single-phase secondary coil. The stator of a single-phase induction motor is joined up to this coil as shown. The motor has a squirrel-cage rotor, which is not shown on the diagram, and which runs quite light as regards mechanical load. As is often the case in such motors, there are two sets of windings on the stator in positions 90 electrical degrees apart. One of these windings is connected across the extreme terminals of the transformer secondary, whilst the other has one terminal to a mid-way tapping of the secondary, and the other to one of the poles of the traction motor the other two poles of whose stator are connected to the terminals of the first-named winding. These connections secure, in the first place, the setting up of the rotating field and split-phase starting of the single-phase induction motor, since the two paths will obviously have different power factors. Then, when the single-phase rotor is rotating, its currents will react on the stator of the traction motor. The action is somewhat complicated, for the E.M.F.s set up by the rotating field and the rotor reactions in the two circuits of the stator of the single-phase motor are in quadrature, because of the coils of these circuits being 90° apart. These voltages, combined with the voltages set up by the secondary of the static transformer, have to be so adjusted by careful design of the single-phase motor and of the traction motor, that the net result produces the required voltages at the terminals of the latter with the not less required proper phase differences. In the example cited the conditions of service are such that the main (three-phase) motor has usually to start under load, and therefore special starting arrangements are necessary, which are more fully described in the section on electric traction.

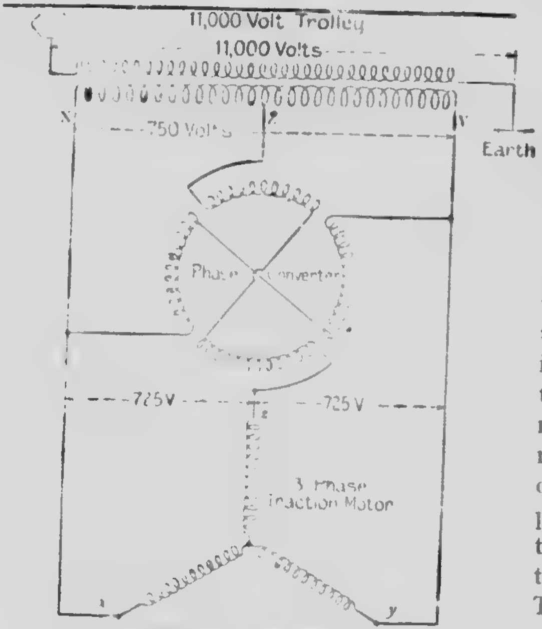

Fig. 973. Single- to Three-phase Connections

It will be noted that the actual transformation of phase is due to the action of the single-phase induction motor which, in this connection, is usually referred to as a "phase converter," and it is so marked in Fig. 973.

Phase and Frequency Changing. Besides changing the voltage and the phase of alternating currents, it is possible by the use of static transformers only to change the frequency also. The practical case where such a change is desirable arises when, for reasons given elsewhere in this book, a low-frequency supply has been set up for power transmission and utilisation and it is found desirable to supply, in addition, a lighting load, for which, as also shown elsewhere, a low frequency is unsuitable. Of course, it is always possible to obtain the higher frequency by means of coupled plant or by rotaries, but this involves the installation of moving machinery requiring attention and a relatively high capital expenditure.

The following method has been developed by M. Maurice Isly (1911), Signor Vallauri, Signor Spinelli (1912), and Mr. A. M. Taylor (1914), from whose paper, read before the Institution of Electrical Engineers, the particulars given below are taken.

The effect obtained depends upon the peculiar shape of the magnetising current curve, shown in Fig. 950 to be necessary to give a sine wave of flux in transformers supplied with a sine wave of voltage. This shape depends, as there shown, largely on the existence of hysteresis, and its peculiarities are (i.) a slower than the sine wave rise at about the point c_3 (*see* Fig. 950), (ii.) a pronounced peak at (c_0), and (iii.) a very rapid fall from c_0 through c_1 and c_2 to zero. The magnitude of these departures from the sine curve depends upon the degree of saturation to which the iron is pushed. By pushing it considerably beyond c_0 on the B B B curve of Fig. 950, the peak can be made sharper and higher, and the flattened part of the rise made flatter and dropped much closer to the zero line as in the curve C in Fig. 974. The next step is to take this current through a coil on a second transformer (Fig. 975), so designed that the current does not nearly saturate the iron, and therefore, since the hysteresis effect is small, the flux wave following the rate of change of the current wave will generate in a secondary coil D wound on it, a current wave also following this rate of change closely. The current wave so obtained is shown at D′

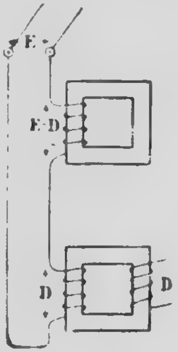

Fig. [illegible]

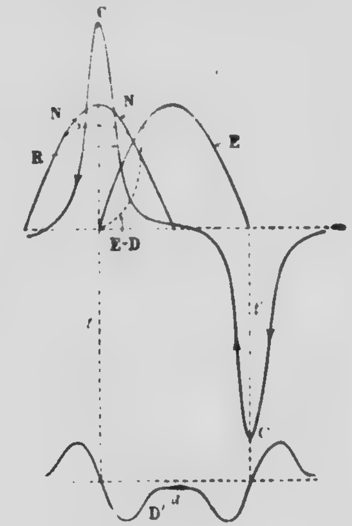

Fig. 974.
Method of obtaining Triple Frequency Currents

at the bottom of Fig. 974. On close study it may be regarded as a sine wave with a very deep, flat-bottomed depression *a* at the place where it should have risen to its maximum, but this depression does not cross the zero line, since the curve from C to C′ above is always falling, though the fall is very much retarded at its mid-section. Had it crossed the zero line there would have been a triple frequency current, since the curve interval between the vertical lines *t t′* is half a period of the original impressed voltage.

The method adopted by Mr. Taylor to obtain a triple frequency current based upon this curve is to superpose three such currents, 120° apart in phase, derived from a three-phase supply. The arrangement finally adopted is shown in Fig. 976, in which three choking coils K are joined in mesh to a three-phase supply, and in each of the meshes is included one-third of the primary winding of a transformer T. The choking coils, which, as explained elsewhere, are the same as transformers but without any secondary windings, are worked to high inductances so as to receive a current wave similar to that shown in Fig. 974. In each phase this current passes through one-third of the winding of T, which works at a very low flux density. The secondary of T is connected to the glow-lamp load L.

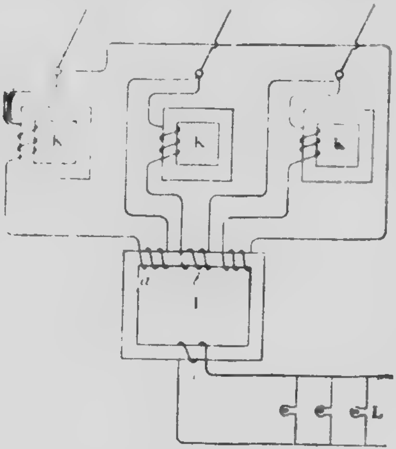

Fig. 976. Three-phase to Single-phase with Triple Frequency.

The result is to superpose three such curves as appear at D in Fig. 974, and an example of such superposing is shown diagrammatically in Fig. 977, in which small disturbing factors are neglected to avoid complicating the curves. The curves of the current in L (Fig. 976), which would be due to each of the coils *a*, *b* and *c*, are shown by the curves *a a a*, *b b b*, and *c c c* respectively, in which a large amount of overlapping is unavoidable. The resultant curve is C C C, which is the current through the lamp load L. This curve is of triple frequency, the current is single-phase, and its voltage is determined by the number of turns on the coil *l*. The general effect of the whole combination is therefore to change the voltage, the number of phases and the frequency of the supply current.

A 7-K.W. set was built on the above lines, and when tested was found to have an over-all efficiency of 86 to 88 per cent., which is of course low. From the data obtained with this set it is calculated that a 500-K.W. set would have an efficiency of 95 per cent., and would compete with a set consisting of step-down transformers and rotary converters with which the lighting load could be supplied with continuous currents. The regulation of the experimental set was found to be good, and several important practical developments of the method are indicated in Mr. Taylor's paper.

X.—THE TESTING OF STATIC TRANSFORMERS

The testing of transformers follows the same general lines which have been set forth in connection with the testing of A.C. generators and motors, but is simpler, inasmuch as all mechanical tests rendered necessary by the machines having moving parts are eliminated and the tests to be made are practically all electrical except those which are concerned with mechanical details of construction, such as the design of the terminals, the efficiency of clamping bands, the lifting and handling arrangements, the oil-tight state of the transformer case

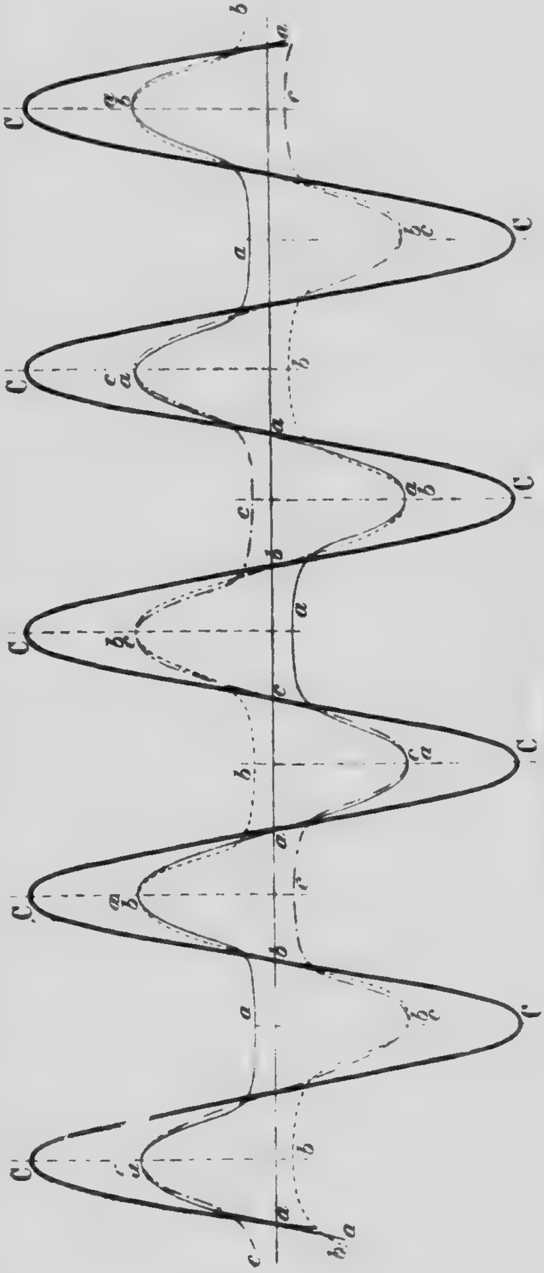

Fig. [illegible].—Static Transformer for Production of Triple Frequency Current.

and arrangements for excluding moisture, the radiation facilities provided, etc., etc.

The chief electrical tests in addition to the ohmic resistance and the insulation are the determination of (i.) the efficiency, and (ii.) the regulation.

Resistance and Insulation. The ohmic *resistance* can be readily measured by the methods described elsewhere, the chief precaution necessary being that the measurement should be made at the working temperature of the transformer, since a rise of 40° C. in the temperature makes a considerable difference in the specific resistance of copper (*see* page 756, Vol. I.).

In testing *insulation*, care should be taken, as previously explained, not to overstrain the insulating materials by using an excessively high testing voltage. The tests required are (i.) primary to secondary, (ii.) primary to earth, and (iii.) secondary to earth. Instead of a direct measurement the usual practice is to put on a sufficiently high A.C. voltage for a definite period and examine for signs of breaking down. This testing voltage for the ordinary windings should not exceed three or four times the working voltage, except for the end windings of high-voltage primaries, which may be subjected to violent electrical surgings and are therefore more heavily insulated.

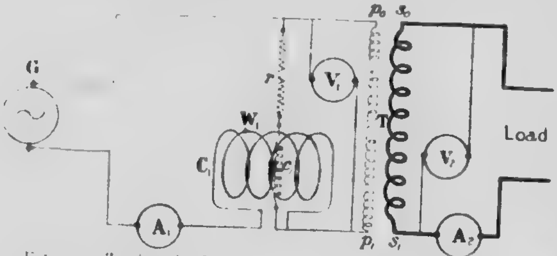

Fig. 978.—Testing the Efficiency of a Single-phase Transformer.

Efficiency. As with generators and motors, the efficiency is tested by measuring the "input" and the "output" under working conditions. The ratio of the latter to the former at any time is the efficiency. The problem is therefore chiefly, given proper conditions of supply and loading, that of the correct measurement of these two quantities, which are both electrical. The principles and methods of such measurement are fully described elsewhere in this book.

Single-phase with Non-inductive Load.—This is the simplest case which can occur in practice. The connections and positions of the instruments are shown in Fig. 978, switches, safety devices, and controlling resistances, etc., not being shown; G is the generator and T the transformer, of which $p_0 p_1$ is the primary and $s_0 s_1$ the secondary winding. On the primary side there is a voltmeter V_1 connected across $p_0 p_1$, an ammeter A_1 in one of the generator leads, and a wattmeter W_1 with its current coil C_1 in the main circuit and its volt coil c_1 bridged across the mains in series with a non-inductive resistance r, the use of which is explained elsewhere. On the primary side there is the non-inductive load (which may conveniently consist of glow lamps), which should be capable of convenient variation over a wide range, a voltmeter V_2 connected across $s_0 s_1$, and an ammeter A_2 on one of the outgoing leads. No wattmeter is shown on this side, as the power factor is unity, and therefore the product of volts and amperes will give the load in watts. If the load be inductive a wattmeter must be used on this side also. A comparison of the above product with the readings of W_1 will give the required efficiency for each load used, and the result should be plotted in a curve with the loads as abscissæ. The power factor on the primary side can be ascertain by comparing the reading on W_1 with the product and the readings of V_1 and A_1 reduced to volts and amperes respectively.

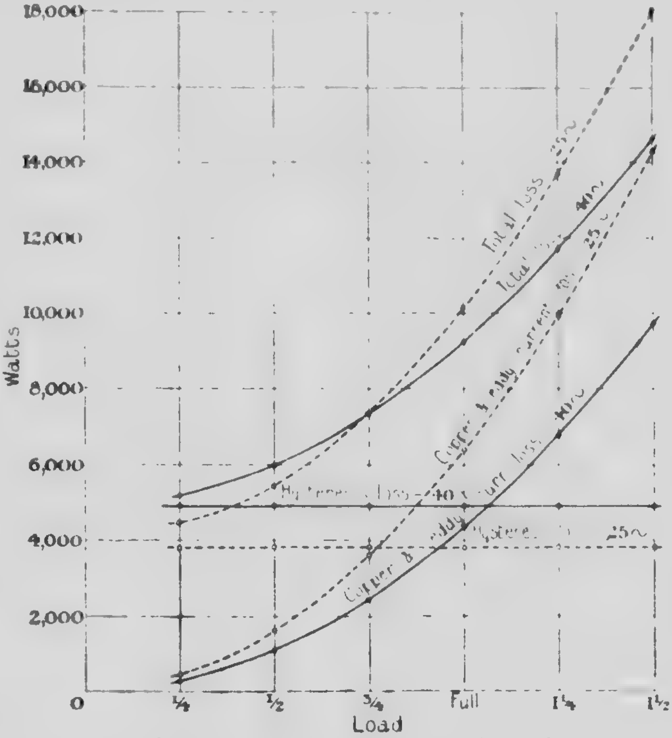

Fig. 379. Losses of Westinghouse Transformers at Various Load

For convenience in a laboratory the circuits are often connected up in the reverse order, a low-voltage generator being used, and the transformer treated as a "step-up" transformer. In that case a non-inductive high-voltage load is conveniently obtained by joining up a sufficient number of glow lamps in series and having several rows of lamps, so that the load can be varied by throwing in and out one or more rows. With either method of working it is essential for a fair test that the voltages employed should be approximately those for which the transformer was designed. These voltages should be marked on the identification plate. Proper precautions must always be taken to protect the experimenter from the danger of making direct personal contact with the high-voltage circuit.

Actual Tests.—As already explained in the section on the theory of the static transformer (page 937), the sources of loss of energy are (i.) hysteresis loss in the iron, (ii.) eddy current loss in the iron, and (iii.) losses due to the ohmic resistance of the copper.

The curves of these losses given in Fig. 979 are for two Westinghouse transformers of nearly equal output, but designed for different periodicities. The transformer to which the full-line curves apply is a transformer with a full-load output of 625 *k*V.A. at 40 periods, whilst the dotted curves are for a transformer with a full-load output of 550 *k*V.A. at 25 periods. The losses are plotted for loads from ¼ load to 1½ times full load. The hysteresis loss depends on the periodicity and the quantity, and the magnetic properties, of the iron, and is independent of load; it is therefore indicated by a horizontal line, being the same at all loads. For the 625-*k*V.A. transformer it is 4,000 watts or 122·5 watts per cycle, and for the 550-*k*V.A. transformer it is 3,800 watts or 152 watts per cycle. If we assume that the transformers are made of similar iron worked at the same flux densities, these figures show that 24 per cent. more iron is used for the lower-periodicity transformer as compared with the higher-periodicity transformer, notwithstanding the fact that the output of the latter is nearly 15 per cent. higher than that of the former. The reason for this has been already explained, but the actual figures are a valuable commentary on the theory.

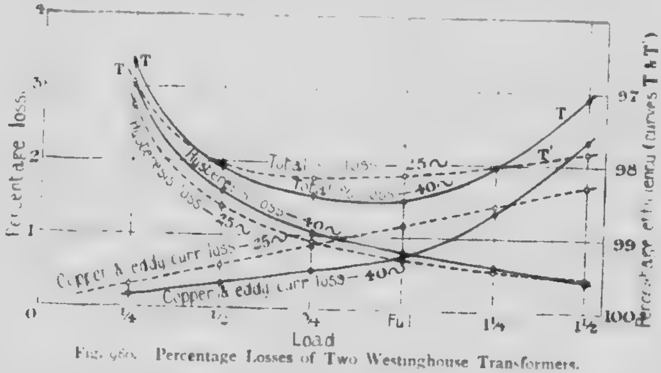

Fig. 980. Percentage Losses of Two Westinghouse Transformers.

The "copper and eddy current" losses are seen to increase with the load; this is because they depend upon the square of the current, and also upon the ohmic resistance of the copper and the iron, which increases as the temperature rises. It being realised that the 550-*k*V.A. transformer is the larger, it will cause no surprise to find that these losses are greater at all loads in this transformer than in the other. For relative "total" loss depends on the loads being smaller at low loads and greater at high loads in the 550-*k*V.A. transformer.

The influence of the difference in the full-load outputs is allowed for by examining the percentage losses for which the curves are given in Fig. 980. The influence of lowered periodicity in increasing the size of the transformer is here more apparent, and should be examined closely in detail as indicating the principles followed in the design of modern transformers. The materials have been so adjusted that for a wide range the loss is less than 2 per cent. in each case, and therefore the percentage efficiency, as shown by the right-hand scale, is over 98 per cent. The large transformer is fractionally less efficient for these loads, but the curves cross at about the 98 per cent. efficiency point, and for very high and very low loads the larger transformer is the more efficient.

One other interesting point should be noted—namely, the magnitude of the total losses (Fig. 979). For full loads they are 10·2 and 9·25 kilowatts respectively, whilst for 50 per cent. overloads they are 18 and 14·0 kilowatts. These figures show emphatically the large quantities of heat which must be carried away if the transformers are to be kept cool. As helping one to realise what is involved, it may be remarked that 18 kilowatts is the output of a 24-B.H.P. steam engine, which would be more than sufficient for the power requirements of many small industrial works.

Single-phase with Inductive Load.—If the load be inductive a wattmeter must be connected on the "load" side as well as on the generator side, since a voltmeter and an ammeter will not measure the power received from the transformer. A convenient inductive load can be provided by an induction motor with or without choking coils in the circuit.

Polyphase Transformers.—The methods of testing efficiency are the same as for single phase with the important modification that polyphase power has to be measured for both the "input" and the "output." The principles and methods of measuring polyphase power are fully dealt with elsewhere (*see* pages 805 *et seq.*, Vol. I., and *infra* in Vol. II.). They probably find their simplest application in the testing of polyphase transformers; considerations of space preclude a repetition of them here.

Regulation.—Next to efficiency, the regulation of the transformer is a matter for careful examination and testing. A transformer with good regulation will, when supplied with constant voltage at the primary terminals, maintain practically the same voltage at the secondary terminals under all conditions of load. If the regulation be not good the voltage will vary, and the determination of this variation under loads of different magnitude and power factor constitutes the examination of the variation.

At first sight it would seem an easy matter to make such tests provided suitable loads are available. All that is necessary is to keep the primary voltage constant, load the secondary with the different loads, and read the voltages at the secondary terminals. The difficulty is that in practice, with good modern transformers, the voltage drop is small, and therefore small differences in readings or small instrumental errors produce a large percentage in the determination of the "voltage drop." It has been explained more than once that the losses assumed in drawing the diagrams in Figs. 949 to 955 were excessive, in order that the influence of these losses might be shown. The "voltage drop" shown on these diagrams is therefore much larger than obtains in practice.

Since it is thus difficult to obtain an accurate measurement of the drop by direct methods, indirect methods are employed, and of these the chief, if not the only one, which is widely used consists in (i.) the accurate determination of the no-load losses, and (ii.) the short-circuit test. The theory of these two tests has already been given (*see* pages 931 to 939).

No-load test.—For this test the transformer and instruments are connected up as already shown in Fig. 978; but the secondary, or load, circuit is open, and therefore the ammeter A_2 carries no current and is superfluous. The test consists in taking readings of A_1, V_1, W_1, and V_2, the reading on V_1 being brought near to the standard voltage for which the transformer is designed. The voltmeter V_2 will give E_2, the full E.M.F. of the secondary circuit, and the voltmeter V_1 will give very nearly E_1, the back E.M.F. of the primary. If the ratio k of the windings is not known, it may be very approximately calculated from the ratio of V_1 to V_2. The current in A_1 is the no-load current I_0 of the last section, and the reading w of the wattmeter W_1 gives the no-load losses. Readings should also be taken above and below the standard value of V_1.

The practical difficulties arise from the small values of the readings of A_1 and W_1, which, with ordinary instruments, are apt to be inaccurate, as the instruments will be working low down on their scales. Of course, special instruments might be used, but it is more convenient to have instruments capable of giving the higher readings required in the short-circuit test.

One precaution which suggests itself, but which, however, increases the above difficulties, is to connect the voltmeter V_1 on the G side of A_1 and W_1, instead of on the T side, as in Fig. 978, in order that the current through V_1 shall not flow through A_1 and W_1, and thus vitiate the low readings, which it might appreciably affect if a hot-wire voltmeter were used.

The difficulty of the very low voltmeter reading is partly overcome by an ingenious suggestion of Dr. Drysdale, shown in Fig. 981, which shows the no-load test arranged with two pressure circuits for the wattmeter, one containing the usual non inductive resistance r of Fig. 978 and the other replacing this resistance by a condenser of capacity C. The

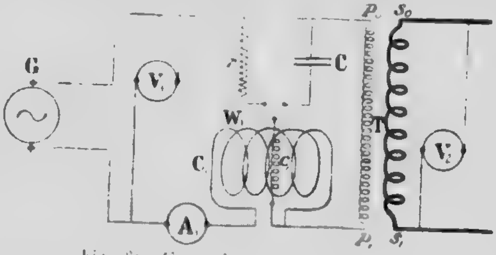

Fig. 981. Connections of a No-load Test.

resistance and condenser should be so adjusted that the same current passes through the wattmeter coil whichever be in circuit. This is approximately the case when $r = \frac{10^6}{p\,C}$. If now readings w_1, V_1, and I_0 be taken with r in circuit, and similar readings w_2, V_1, and I_0, with C in circuit, then, assuming that V_1 and I_0 are the same for both sets of readings, we know that

$$w_1 = V_1\, I_0 \cos\phi$$
$$w_2 = V_1\, I_0 \sin\phi$$

but since ϕ the angle of lag is nearly 90° we know that w_2 will be much larger than w_1 and its value more reliable. The current $I_0 \sin\phi$ is the magnetising current I_m of Figs. 949 and 952, and its value is therefore formed directly from

$$I_m = \frac{w_2}{V_1}$$

and the angle of lag ϕ can be determined from

$$\text{Sin}\,\phi = \frac{I_m}{I_0} = \frac{w_2}{V_1\, I_0}$$

but this latter requires I_0 to be fairly accurately known. With V_1, I_0, and ϕ known, a check is obtained on the low reading w_1 of the actual power as given by the wattmeter reading.

The reading w_1 gives the core loss, that is the hysteresis and eddy-current losses. The resistance R_0 of the equivalent inductionless shunt coil which would represent this loss is given by

$$R_0 = \frac{V_1^2}{w_1}.$$

Similarly the value of the equivalent resistance-less inductance, is given by

$$p\,L_0 = \frac{V_1^2}{w_2}.$$

Short-circuit Test.—The theory of this test has been given at page 939. The connections of the transformer and instruments are shown in Fig. 982. In addition, some means, either by variable choking coils or resistances, are required for controlling and adjusting the voltage V_1. The test consists in raising the voltage V_1, which will be less than the standard voltage for the transformer, until currents approximating to and exceeding the full-load current of the secondary circuit are shown by the ammeter A_2. Readings are taken simultaneously on all the instruments for various values of V_1, and the equivalent resistance and reactance calculated. Some experimenters prefer not to

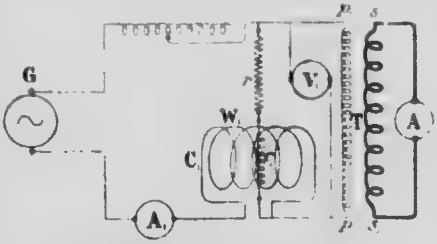

Fig. 982. Connections for a Short-circuit Test

introduce the resistance of the ammeter into the secondary circuit, but to put a heavy copper "short" across the terminals. In this case the primary current properly interpreted (*see* page 933, *footnote*) is used to indicate when the transformer is fully loaded. A reference to Fig. 952 will show that this is possible.

The whole of the measured voltage v_1 is the "voltage drop" for the various load currents, and the equivalent reactance is, as already shown, given by

$$\textit{Equivalent reactance} = p\text{L} = \frac{v_1 \sin \phi}{I_1}$$

the angle of lag ϕ being given by the equation

$$\text{Cos}\, \phi = \frac{w}{v_1\, I_1}.$$

Another method of calculating the equivalent reactance is to use the equation

$$p\text{L} = \frac{\sqrt{v_1^2\, I_1^2 - w^2}}{I_1^2}.$$

The equivalent resistance is obtained from the equation

$$\textit{Equivalent resistance} = \text{R} = \frac{w}{I_1^2}$$

where w is the power shown by the wattmeter reading.

Regulation Curves.—Assuming the iron losses to be constant and the equivalent reactances and resistances to be as above, it is now possible by applying the principles set forth in the last section to plot curves showing the regulation of the transformer for all loads at various power factors from unity downwards. Some of the values so obtained should be checked by direct experiment.

The results of such experiments are shown in Figs. 983 and 984, for the two transformers for which the efficiency curves and details of losses have been given in Figs. 979 and 980. In Fig. 983 the percentage regulation at different power factors is plotted against the load from ¼ to 50 per cent. overload. As before, the dotted curves are for the larger (550 *k*v.a.) transformer at the lower periodicity (25 ∼), and the full-line curves for the smaller (625 *k*v.a.) transformer at the higher periodicity (40 ∼). Within the ranges of load mentioned the dotted curves are straight lines, and the deterioration of the regulation under the influence of the lowered power factor is very marked in both sets of curves. The full-line curves appear to be made up of two straight lines, the falling off of the regulation being much more rapid with increase of load in the case of overloads than for loads within normal limit. The writer has not sufficient knowledge of the details of the two transformers to explain this.

The actual values of the regulation should be carefully noted, and especially that for full load at unity power-factor, the regulation is within a little over 1 per cent. for the larger transformer and as low as 0·7 per cent. for the smaller transformer.

The influence of the power factor at full load and for a much wider range is shown more clearly in Fig. 984, in which the percentage regulation is plotted against the power factor from unity power factor down to 0·3. It should be noted that the influence of the fall of the power factor on the regulation is at first great, the change in regulation being from about 1 per cent. to about 3 per cent. between power factors 1 and 0·7; for lower power factors the change is not serious. Below 0·7 power factor the curves are quite flat, but the smaller transformer is the more affected.

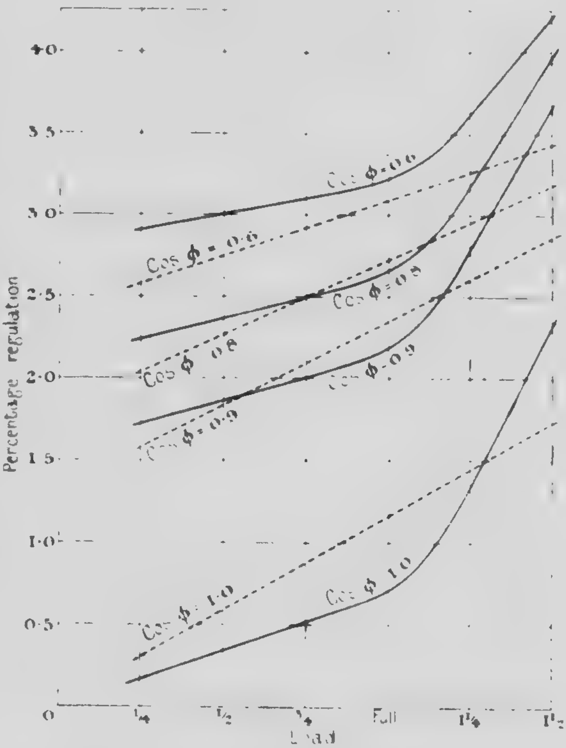

Fig. 983.—Regulation at Different Power Factors and Loads.

XI.—TRANSFORMERS FOR SPECIAL PURPOSES

The transformers described in the preceding pages are what may be conveniently described as power transformers designed for the transformation of larger or smaller amounts of power under the conditions most generally prevailing at the present time. The descriptions given have not exhausted all the varieties of large power transformers in common use, and, as

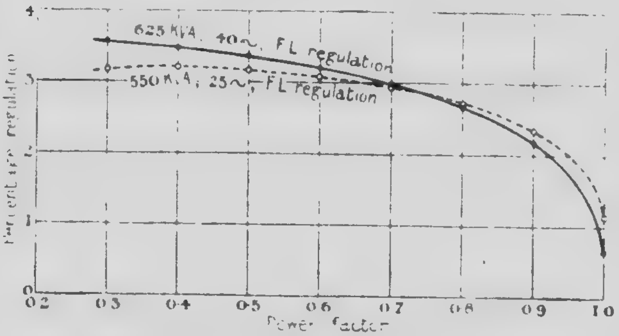

Fig. 984.—Full-load Regulation at Different Power Factors.

opportunity occurs, it is proposed to return to the subject in connection with special applications. The principle of the static transformer, however, is so flexible and adaptable that it is applied to an almost infinite variety of purposes in the practical applications of electricity to the service of man. These applications, especially those in telegraphy and telephony, are referred to under their special headings, but there are one or two outstanding applications in heavy electrical work which may be dealt with here, as may also the modifications necessary in designing very high-voltage transformers, whether required for actual power transformation in a power transmission scheme or simply for testing purposes.

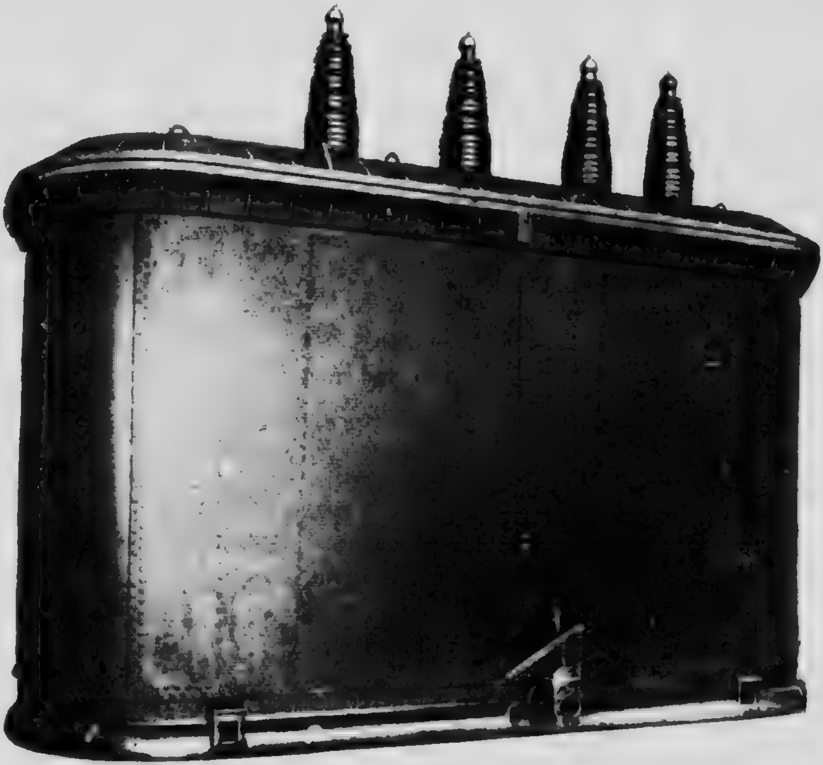

Fig. 985. A 14,000-kv.a. 100,000-volt G.E. Shell Transformer in its Tank.

Reference is therefore briefly made in this section to the following types:—

(i.) High-voltage transformers for testing or for power transmission.
(ii.) Instrument transformers for high-voltage working.
(iii.) Constant-current transformers.
(iv.) Auto-transformers

High-voltage Transformers.—When the voltage on the high-voltage coils of a transformer exceeds, say, 70 kilovolts, construction difficulties of a new order intervene similar to those which are met with in the equipment of transmission and other apparatus at these voltages. Such transformers are constructed for two distinct purposes: (i.) As step-up and step-down transformers on high-voltage transmission schemes; and (ii.) as step-up testing transformers to obtain high voltages for testing purposes.

As an example of the first class, Fig. 985 gives an external view and Fig. 986 a view with the oil tank removed of a transformer built in 1910 by the General Electric Company for the Shawinigan Power Co. of Canada, and which at that time was the largest transformer built. It is a 14,000-*k*V.A. transformer, designed to take 100 kilovolts on its high-voltage terminals.

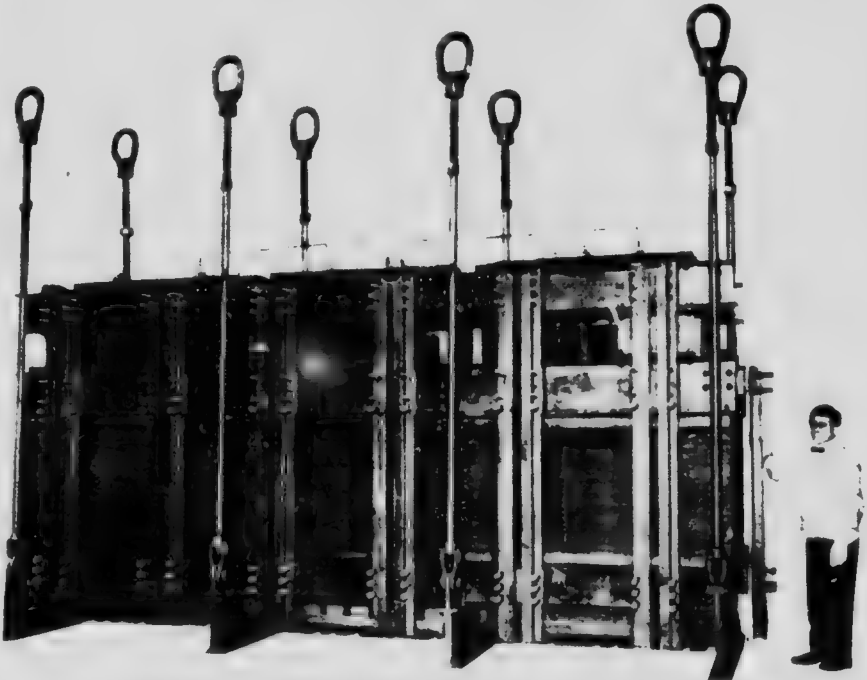

Fig. 986.—The G.E. High-voltage 14,000-*k*V.A. Transformer without Oil Tank.

The transformer is three phase, of the shell type, and in its case, as shown in Fig. 985, the over-all dimensions are 23 ft. long, 8½ ft. wide, and 18 ft. high to the top of the high-voltage terminals. The volume of oil used to charge the transformer is 11,000 gallons, and the total weight of the complete transformer is 480,000 lb., or 214 tons. More recently the same company has built a 50,000-*k*V.A. three-phase 2 to 1 auto-transformer.

A *testing transformer* designed to supply a testing voltage of 500,000 volts, and capable of attaining a pressure of 600,000 volts, has been built by the Oerlikon Company, of Oerlikon, Switzerland. An external view of it is given in Fig. 987. Though intended for testing purposes only, the continuous rated load is 500 *k*V.A., and it can carry a momentary load of 2,000 *k*V.A. One of the difficulties of building a small capacity transformer for these high pressures arises from the great number of turns required on, and the very small current that would flow in, the high-voltage circuit at full load. Thus if the capacity were only 5 *k*V.A. the current at full load for a pressure of 500 *k*V. would only be 10 milliamperes, and a conductor calculated at the current densities used in ordinary transformer design would be much too small to be practicable. The insulation would be costly and the space factor very low. Even in the transformer shown in Fig. 987 the full-load current is only 1 ampere at 500 *k*V. Another factor which increases the over-all size of the transformer, even for the rated capacity, is the space that has to be provided to secure effective insulation.

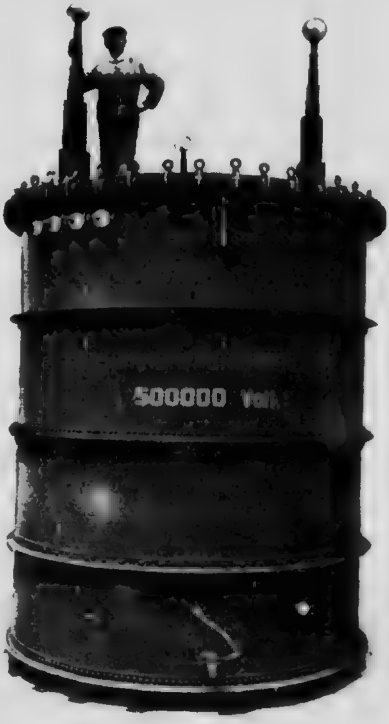

Fig. 987.—Oil Tank of Oerlikon 500,000-volt Testing Transformer.

The Oerlikon transformer of Fig. 987 stands nearly 19 feet high to the top of the terminals; the oil tank is 11 feet 9 inches high and 10 feet 9 inches in diameter. The transformer itself weighs 10 tons and the oil tank 5 tons when empty, and 24 tons when filled with oil. Thus the total weight of the transformer ready for working is about 34 tons. The low voltage circuit, which in this case is the primary circuit, is designed to carry 1,000 amperes at 500 volts. The voltage is controlled by an induction regulator (*see* page 1298) in the primary circuit constructed to give a continuous variation of the secondary voltage from 0 to 500,000. At full primary voltage the ratio of transformation *k* is therefore 1 to 1,000.

The top of the transformer is shown on a larger scale in Fig. 988, in which can be seen more clearly the details of the high-voltage terminals T T. The insulation appears to consist of successive tubes of insulating material. The smaller third terminal *t* is connected to the mid-point of the secondary winding, and is usually earthed; but for special tests it can be insulated. The low-voltage terminals are shown at the top of Fig. 985, immediately below the clamping ring.

The transformer itself, without the oil tank, is shown in Fig. 989, which is reproduced from a photograph kindly supplied by the Oerlikon Company. Several interesting details can be clearly made out. The most interesting are perhaps the subdivision, and the arrangement, of the secondary or high-voltage winding and the high-voltage insulating arrangements generally. The high-voltage winding would appear to be built up of a series of flat coils with slabs of insulating material between. There are 62 such coils on each limb, or 124 coils in all, which, when working at 500,000 volts, gives about 4,000 volts per coil. Starting from the terminal, which is joined to the central coil on each limb, the coils are connected in successive pairs above and below the median plane by carefully insulated vertical conductors well removed from the windings. The whole of these conductors on the right-hand limb, and some of those on the left, can be seen in the figure. Thus the maximum stress between the coils on the two sides of each insulating slab will be about 8,000 volts (R.M.S.) instead of 4,000 volts, which would be the maximum stress if the coils were connected each to the neighbouring coil in simple series; but the method adopted has the advantage that the maximum potential stress is brought to the middle of the limb, and is, therefore, removed to the greatest possible distance from the exposed metal work at the top and bottom of the transformer.

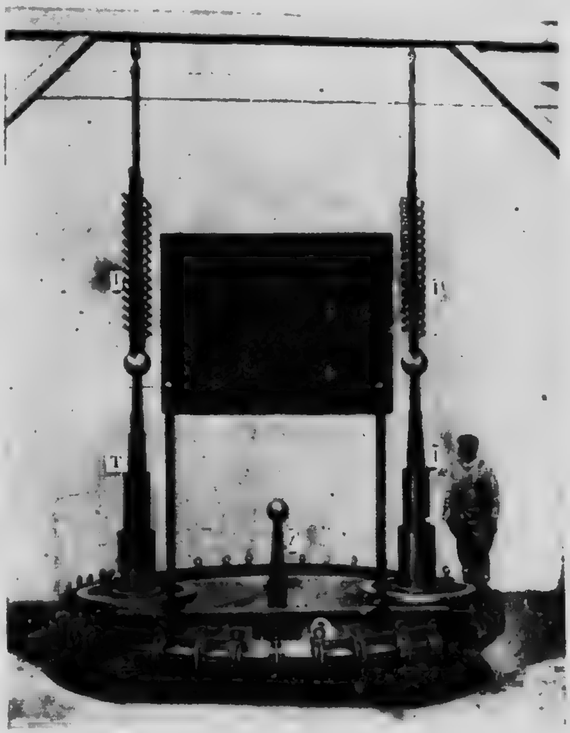

Fig. 988. Top of Oerlikon High-voltage Transformer

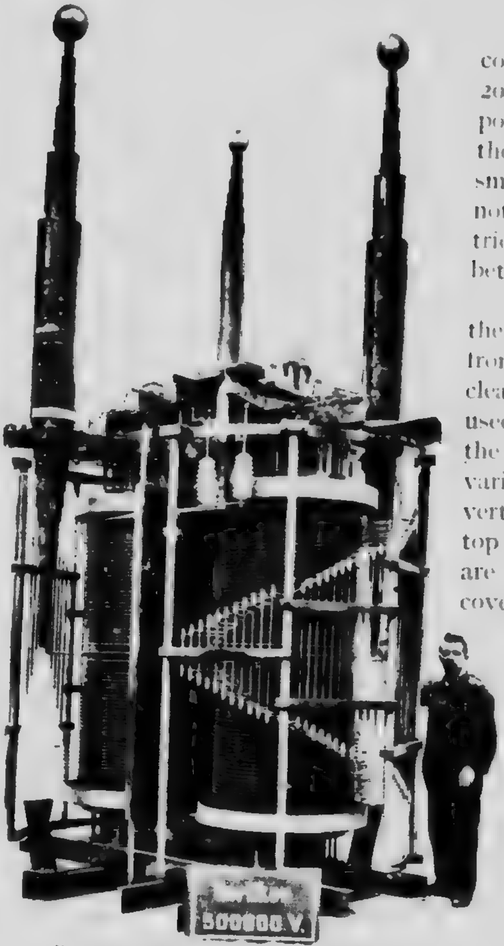

Fig. 9[illegible]. Oerlikon 500 kv. Testing Transformer.

The main terminals rest upon corrugated porcelain insulators about 20 inches long, and are also supported by insulating material from the framework at the top. The smaller mid-terminal is also well but not so heavily insulated, and is electrically connected to the cross-over between the two limbs.

Some idea of the cross-section of the magnetic circuit can be obtained from the bottom yoke, which is clearly visible. Channel iron is freely used, top and bottom, to strengthen the transformer and to carry the various necessary supports. All vertical metallic rods passing from top to bottom outside the windings are for obvious reasons carefully covered with insulating material, and a vertical insulating shield is interposed between the two limbs.

The simplest way of measuring the high voltages is by means of a voltmeter in the primary circuit, the voltage read being multiplied by an appropriate constant. This method is, however, indirect and unsatisfactory. In the Oerlikon transformer the measurement is made by an adjustable spark gap connected to the secondary terminals as shown in Fig. 988. The scale of voltage used with [illegible] electrodes shown is interesting and is as follows:—

A [illegible] gap sparks at 100,000 volts
,, 514 ,, ,, 200,000 ,,
,, 774 ,, ,, 300,000 ,,
,, 1,050 ,, ,, 400,000 ,,
,, 1,320 ,, ,, 500,000 ,,
,, 1,580 ,, ,, 600,000 ,,
,, 1,850 ,, ,, 700,000 ,,

The distance apart of the electrodes is read off on a graduated scale bolted to the top of the tank.

One disadvantage of this method of measurement is the dangerous surgings that are set up in the transformer by the sudden passing of the spark when the sparking voltage for which the electrodes are set is reached. To damp down these surgings the testing electrodes are connected to the main terminals through carbon resistances seen above T T in Fig. 988. One of these resistances is shown on an enlarged scale in Fig. 990. It acts by quenching the oscillations as explained elsewhere. The resistances are bolted to the terminal spheres and are suspended with them by insulating tubes from the iron frame seen in Fig. 988.

To balance the capacity current when the transformer is used to test cables or insulators of large capacity, a choking coil with variable inductance is placed across the low-voltage terminals, and is so adjusted that the current flowing is only sufficient to make good the losses.

High-voltage (200 kilovolts and over) transformers are now made, especially for testing purposes, by several well-known British and American firms, but considerations of space preclude us from carrying the matter further.

Instrument Transformers. In the section on "Generating Stations," and elsewhere, references have been made to the employment, especially on high-voltage circuits, of transformers used solely for the purpose of supplying current to the measuring and other instruments and the safety devices on the switchboard and elsewhere. The use of such transformers has the double advantage of keeping the parts of the protected arrangements clear of dangerous voltages, and frequently it simplifies the design of the protected apparatus. A further material advantage is that the leads connecting the secondary coils of the transformers with the instruments, etc., need only be of small cross-section and not expensively insulated; they are therefore inexpensive, easily handled, and can be neatly and expeditiously run. Moreover, with such leads the apparatus served may be placed in the most convenient position determined by other considerations, and the necessity of running leads to it need not modify the design.

These transformers therefore play an important part in modern electrical work. They are mainly of two types: (i.) current transformers, and (ii.) potential transformers, the first supplying measuring currents to all apparatus, whether measuring or protective, the action of which is to depend upon the magnitude of the current passing in the high-voltage circuits, and the other

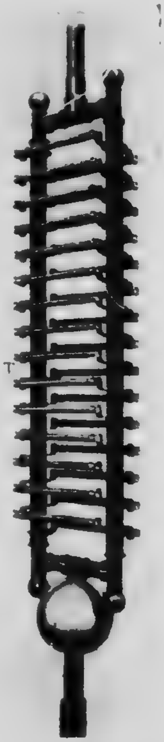

Fig. 990. Oerlikon Damping Resistance for Spark Discharge.

supplying currents to the apparatus whose action is to depend on the voltage.

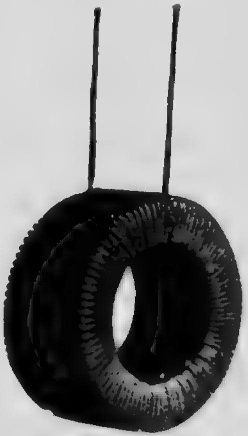

Fig. 991. Secondary Winding of a Current Transformer.

It may first be pointed out that still another advantage of these transformers is that the secondary windings on both types may be standardised. Thus for the current transformers the standard maximum or the normal secondary current may be 5 amperes whether the maximum or the normal primary current be 30 amperes or 3,000 amperes. In the potential transformers also the maximum or the normal secondary voltage may be 100 volts whether the corresponding voltage of the particular primary circuit for which the transformer is designed be 2,000, 10,000, or 20,000 volts. This standardisation enables all the apparatus to be served, whether measuring or protective, to be standardised, the only variation being in the *marking* of the scales of the measuring instruments with the currents or voltages of the primary winding instead of the actual currents or voltages acting in those instruments.

Current Transformers.– It will readily be inferred from the foregoing that the primary of a current transformer is placed in series with the main current for which it is designed, taking the place there of the particular apparatus to be served. The secondary of the transformer is then connected to the ammeter, trip coil, or other apparatus placed in its external circuit, which is one of low impedance.

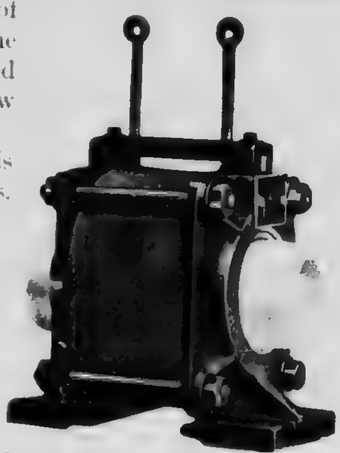

Fig. 992. – Ferranti Current Transformer without Primary Conductor.

The theory of these small transformers is similar to that developed for larger ones. For instance, the primary and secondary currents are not in phase. This is of no consequence for ammeter or relay working, but if the secondary current be used in a wattmeter this phase difference must not be overlooked. We return to the subject in the chapter on "Measuring Instruments."

The most striking instances of the differences between current transformers and the transformers previously described are perhaps found amongst those in which the primary current is so large that the main conductor need only be passed once straight through the magnetic circuit of the transformer without any of the usual "winding."

A good example is given in Figs. 991 and 992, in which Fig. 991 represents the secondary winding which completely encloses the laminated magnetic core, which is in the form of a ring, the two ends of the winding being brought out quite simply. This ring can be slipped over the insulated cable, which encloses the main conductor, proper care being taken not to damage the insulation. In Fig. 992 the wound core has a porcelain bush to insulate the secondary winding from the primary; it is clamped up between two end-plates, these plates having feet for fixing. The current transformers as manufactured by Messrs. Ferranti, Limited, are of a standard type. The standard maximum secondary current is 5 amperes, and the normal load on the transformer is 20 volt-amperes. The transformers are built for maximum primary currents from 400 to 1,000 amperes. The porcelain bush shown is intended to insulate voltages up to 1,250 volts; for higher voltages a heavier type of bush is used.

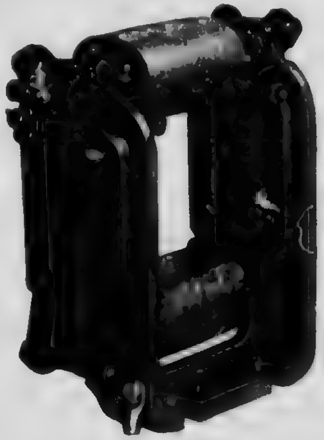
Fig. 993.—Quadrangular Magnetic Circuit for Ferranti Current Transformer.

Another standard type of secondary winding made by Messrs. Ferranti is shown in Fig. 993. The magnetic circuit is quadrangular, and the secondary coil wound in four sections, the ends of the winding being brought to suitable terminals. Suitable porcelain bushings are provided for a "straight-through" primary conductor passing through the central opening, or the secondary can be slipped over a main circuit conductor, proper precautions being taken as regards insulation. For currents up to 4,000 amperes the opening is 3½ inches square, and from 5,000 to 10,000 amperes it is 5 inches square, with other dimensions in proportion. The larger size weighs 50 lb. net.

Transformers of the "ring-core" type, as it is called, are also manufactured by The British Thomson-Houston Company, as shown in Figs. 994 and 995. The magnetic core, with its secondary coil, is slipped over a porcelain tube not less than half an inch thick, through which the primary conductor is to be passed. The transformer can be supplied with or without a primary conductor. In Fig. 994 the primary conductor is a copper rod with suitably worked ends

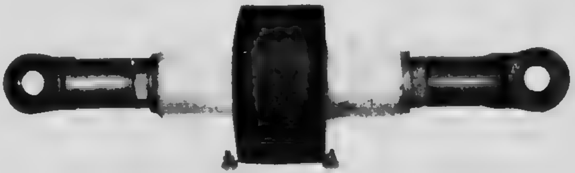
Fig. 994.—B.T.-H. Unmounted Current Transformer with Primary Conductor.

for connection to the main circuit. In Fig. 995 such a rod is also shown, the other parts of the transformer being mounted on a bracket provided with slotted feet for clamping. In both cases the ends of the secondary winding are brought to terminals at the top and bottom of the cylinders. The standard sizes of Fig. 994 type are for maximum primary currents from 100 to 1,000 amperes, with a capacity from 5 to 15 volt-amperes, whilst in Fig. 995 the currents may be from 100 to 3,000 amperes, and the capacity from 5 to 75 volt-amperes. They are both for circuits where the voltage does not exceed 2,000 volts to earth. For higher voltages heavier insulation is provided.

[illegible] B. T. H. Mo[illegible] [illegible] Transformer w[illegible] [illegible]

For high voltages the currents, even for a considerable amount of power transmitted, are comparatively small, whilst the insulation difficulties are enhanced. The small currents necessitate a "multi-turn" primary in the current transformer, such as is shown in Fig. 996, which is an illustration of a transformer manufactured by The British Thomson-Houston Company. The primary coil, terminals T_1, T_2, of the requisite number of turns is passed through two porcelain tubes, the lower one of which passed through the core of the ring-wound secondary terminals t_1, t_2, which is similar to the secondaries described above. This is intended for currents up to 300 amperes and voltages not exceeding 7,000 volts to earth. The transformer is $18\frac{1}{2}$ inches long, $6\frac{7}{8}$ inches wide, and $9\frac{5}{8}$ inches high.

Fig. 996.—B.T. H. High-voltage Current Transformer with "Multi-turn Primary.

Potential Transformers. In potential transformers the chief difficulty of the design lies in providing efficient and lasting insulation, because the full potential difference of the high-voltage lines is necessarily placed across the terminals of the instrument. In other respects there is nothing very special in the design except the point already mentioned of the standardising of the secondary pressure to a maximum of 100 volts for the normal working primary voltage, for which the particular transformer is designed.

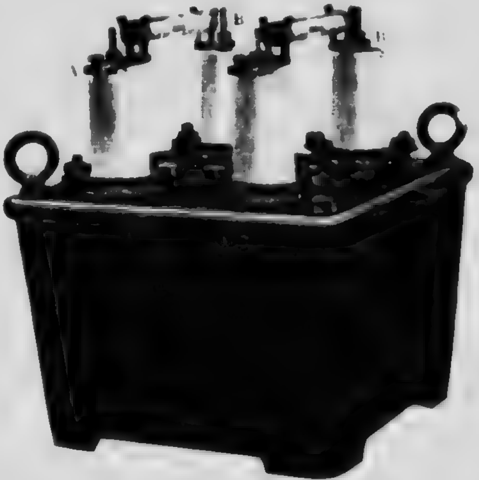

Fig. 997.—Ferranti Potential Transformer with Fuses.

The external appearance of a single-phase Ferranti high-voltage standard potential transformer is shown in Fig. 997. It is of the oil-insulated type, and two high-voltage terminals are provided on each side of the insulating barrier which separates the opposite poles of the primary circuit. One of these A on each side is for the lead from the main circuit, and the other B is the terminal of the primary winding. The two are connected by a safety fuse contained in an insulating tube and lying between suitable clips.

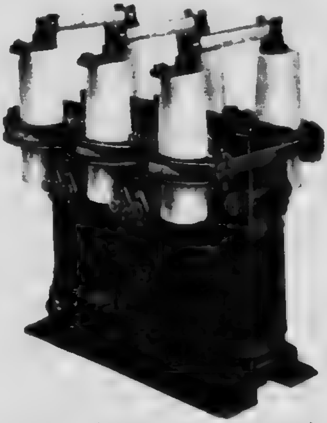

Fig. 998.—Ferranti Three-phase Potential Transformer.

The transformer is of the core type and the primary high-voltage winding is divided into a large number of sections placed next to the core, from which they are separated by a mica tube made by wrapping mica round a former and then taping and impregnating it with a material quite unaffected by the insulating oil. Each section of the winding is former wound with double cotton-covered wire, very tough leatheroid sheet being inserted between the layers. The section is then dried in a hot vacuum chamber, impregnated with varnish under pressure, and again dried, being then wrapped with insulating tape and cloth and again dried and impregnated. The completed coil is sometimes wrapped with tinfoil, which forms an additional source of safety as an earthed shield. A second mica tube slipped over the primary winding separates it from the secondary winding, the construction of which is quite simple. In working, one pole of this secondary winding should be earthed to minimise the effects of electrostatic charges between the primary and secondary windings, which, regarded as the two plates of a condenser, have a distinct electrostatic capacity. With the transformer connected to a high-voltage circuit, the secondary windings, if well insulated, may become charged to a very high and dangerous potential, but with one point earthed this danger is reduced to a minimum.

The above standard transformers are made with capacities of 10, 50, and 150 volt-amperes, with an ample margin for short overloads, such as may occur when used for synchronising. The range of voltages for which they are standardised runs from 1,000 to 40,000 volts.

A similar three-phase potential transformer without its oil tank is shown in Fig. 998. It will be seen by comparison with Fig. 894 that it follows closely the design of the large power transformers previously described. It may therefore be well to state that the transformers without their cases vary, according to the primary voltage, from 11 to 19½ in. in height, from 9 to 14½ in. in length, and from 6½ to 10 in. in width, whilst their weights vary for single-phase types from 30 to 76 lb., and for three-phase types from 45 to 105 lb. without fuses or tanks. The high-voltage circuits are protected by fuses outside the oil tank, as in Fig. 997. The three terminals of the secondary or instrument winding and also an earthing terminal, can be seen on the front in Fig. 996. The coils are star connected unless otherwise required.

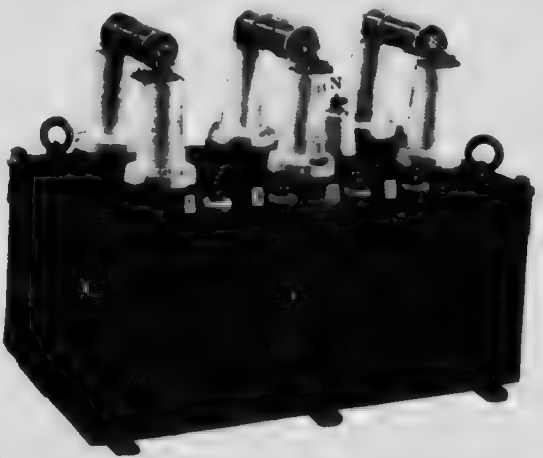

Fig. 999.—Three-phase Air-insulated B.T.-H. Potential Transformer

A British Thomson-Houston three-phase potential transformer is shown in its case in Fig. 999. The transformer is air-insulated, but oil-insulated transformers of the same type are also available. It will be noted that in general appearance it is very similar to the transformers just described, and therefore no detailed description is necessary. The circuits are connected "star-star" with the neutral point brought out. The neutral high-voltage terminal can be seen at N, whilst *s s s* are the secondary terminals with *n* for the terminal connected to the secondary neutral point.

Constant-current Transformers.—A curious illustration of the flexibility of the static transformer is the fact that it is possible to design a transformer which, within certain limits, shall have a nearly constant current in its secondary coil, whatever voltage is demanded to supply that current to the external load. In other words the voltage at the terminals of the secondary, and therefore the E.M.F. in its coils, are variable quantities which automatically adjust themselves so as to supply the same current to the external circuit, whether that circuit requires a high or a negligible voltage for this purpose.

This fact, as mentioned in the 1893 edition of this book, was taken advantage of by Professor Elihu Thomson, who designed a *constant-current transformer* for the purpose of supplying current to a variable number of arc lamps in series. The general design of such a transformer is shown diagrammatically in Fig. 1,000, which is copied from the edition mentioned. The primary and secondary coils are on separate cores, which alone would tend to increase the values of the leakage fields N_1 and N_2 (*see* page 934), a tendency which is increased by supplying a third unwound core with a non-magnetic gap at A. The result is a very leaky transformer, for which the vectors e_{s1} and e_{s2} of Fig. 952 will be relatively very much larger than in an ordinary power transformer. In consequence, it is possible to have constant voltage and variable current in the primary, and nearly constant current with variable voltage in the secondary.

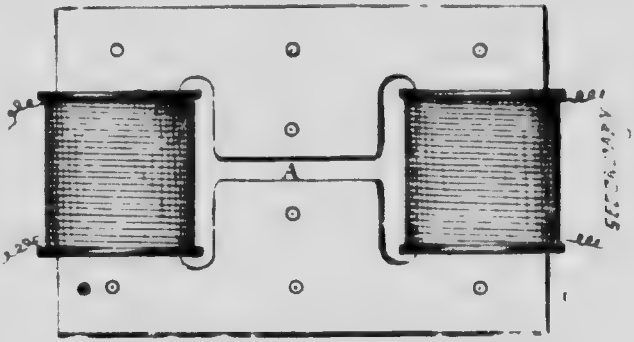

Fig. 1,000.—Elihu Thomson's Constant-current Transformer.

The subject does not lend itself to the simple method of explanation adopted in the elementary theory of the ordinary transformer, since the quantities are subject to greater variations. The fluxes N, N_1 and N_2 will be nearly constant, because of the constant voltage applied to the primary, but $(N - N_2)$ will not be constant, because of the extra voltages generated in the secondary; moreover, the phase relations of these quantities will be different. Suppose the secondary to be loaded with a few glow lamps in series, and that one of these be short circuited, there will be a momentary increase of current, which will diminish the effective flux through the secondary core. This increase, however, will be throttled by the large value of L_2, the inductance of the secondary, and, within limits, the effective flux will settle down to a lower value corresponding to the smaller voltage now required at the terminals, the phase relations also changing including the relative values of the wattless and working currents. Such a transformer has, of course, very bad regulation, the voltage drop at all loads being large. In fact, it is by the variation of this bad regulation that it attains the desired result.

Auto-Transformers.—The principle of the auto-transformer has already been explained at page 721, and in the following pages illustrations have been given of such transformers designed for the purpose of starting induction motors. It is therefore unnecessary to pursue the subject farther here except to remark that if the transformer is to be used to supply currents for longer periods than required for starting purposes the copper in the windings which act as a secondary coil must be of sufficient cross-section to carry these heavier currents. The principles of such design are not different from those already explained.

The auto-transformer has also an important application for balancing purposes in power-distribution systems, in which its flexibility is found very useful for balancing purposes. Its application for such purposes is dealt with on page 1348, and the following pages.

Other Applications of Transformers. As mentioned more than once in the preceding pages, the static transformer is so simple in principle and so flexible in its details that its applications are almost infinite. Even for power purposes the preceding pages have not nearly exhausted the subject. Further modifications will, however, be more conveniently dealt with in connection with the special application in which they play an important part, more especially in the section on distribution, where, in addition to uses already mentioned, they are referred to as acting—

(*a*) as *voltage regulators* (*see* page 1207).
(*b*) as *balancers* to counteract the variations of voltage caused by unbalanced loads (*see* page 1307),
(*c*) as choking coils or *reactances* designed to protect an installation or system from the evil effects of short circuits and surgings (*see* page 1260), and
(*d*) as *static balancers* on three-wire c.c. systems (*see* page 1310).

CHAPTER VIII

KINETIC TRANSFORMERS

In this chapter the second general type of transformers, according to the classification adopted on page 859, is dealt with. This type consists of transformers with moving parts, or rotors, and therefore appropriately known as "kinetic" transformers.

I.—CLASSIFICATION OF KINETIC TRANSFORMERS

The kinetic transformers in ordinary use in modern electrical engineering work have been classified in Vol. I. (*see* page 575), and the history of their development and the principles underlying their action have also been explained (*see* Chapter XVII., Vol. I.). It is necessary, therefore, only to recapitulate here that they fall into the following categories:

(i.) Coupled motors and generators.
(ii.) Motor generators properly so called, i.e. single machines.
(iii.) Rotary converters or rotaries.
(iv.) Motor converters.
(v.) Permutators.

Coupled Motors and Generators.—Plant consisting of a motor of suitable type and speed, coupled to one or more generators (with exciters and starters sometimes added), is very widely used for a variety of purposes. The outstanding properties and characteristics of the motors and generators available have been very fully discussed in the preceding pages. The arrangement is extremely flexible; but the advantages and disadvantages of a particular combination for a special purpose, such as ordinary substation working, balancing on a three-wire system, boosting, etc., are best considered in connection with that purpose. It has, therefore, been decided to postpone the further consideration of these combinations until their applications are being dealt with, and for the present to refer the reader to the sections cited above.

Motor Generators.—This term is very commonly, though not very happily, applied to the combinations referred to in the last paragraph. It would be better restricted to that type of continuous-current transformer which consists of a single machine on the rotor of which there are wound a "high-voltage" and a "low-voltage" circuit, each with its own commutator. One of these circuits, when supplied with continuous currents of the proper voltage, acts as a motor circuit, driving the rotor against frictional forces and against the forces developed by the generator action of the other circuit.

Such machines fulfil a useful purpose, but are not very often required, and are, therefore, not very widely used. In one of their chief applications, namely as balancers, they have been to a great extent superseded by the coupled plant referred to above and by other combinations which will be referred to in due course. It is, therefore, not necessary to add here anything to what has already been set forth in Vol. I. (*see* pages 631 to 635).

Permutators.—These are machines which convert alternate currents into continuous currents of a definitely related voltage. Both the stator and the ordinary rotor are fixed, and the motion is confined to sets of synchronously rotating brushes. The method has not, as yet, come very widely into use, and the description of the Rougé-Faget permutator at page 643 of Vol. I. will suffice at the present stage of the development.

II.—ROTARY CONVERTERS

The neral construction and the principles underlying the working of rotary converters or, as they are more briefly called, "rotaries," have been fully explained in Vol. I. (*see* pages 635 to 641). Working from the alternate-current side, the machine may be regarded as a synchronous alternate-current motor combined with a continuous-current dynamo, whilst when working in the opposite direction it is a continuous-current motor combined with an alternator. It has, therefore, the properties and peculiarities of all these machines and, as a consequence, actual practice reveals developments which require careful handling.

The chief function fulfilled by rotary converters in modern electrical engineering is the conversion of alternate-current power into continuous-current power. This function is so well carried out by rotaries and similar plant that it has been suggested that circumstances may arise in which it may be preferable to generate low-voltage alternate-current power and convert the whole of it for local distribution into continuous-current power rather than generate continuous-current power directly. Without endorsing this suggestion, it may be readily conceded that the rotary converter and its closely related rival, the motor converter, are of outstanding value to engineers, and can claim a large share in the development of the applications of electrical power to the service of man.

In theory there is no restriction on the kind of alternate-current power, whether monophase or polyphase, which can be handled by rotary converters, but in practice, polyphase power, most frequently six-phase power, is dealt with. Some years ago large rotaries for two-phase and three-phase currents were quite common; but, as will appear in the sequel, certain practical advantages can be obtained by increasing the number of phases, and in the closely-related motor converter as many as twelve phases are quite commonly used.

A good idea of a large modern rotary converter fitted with an A.C. starting motor can be obtained from Figs. 1,001 and 1,002, which are taken from a 1,000-kilowatt machine built by the British Thomson-Houston Company. The machine is 12 ft. 8¾ in. long, 10 ft. wide, and stands 7 ft. 9½ in. high, measured from the floor level on which the base plate rests, the external diameter of the magnet yoke being 8 ft. 5 in.

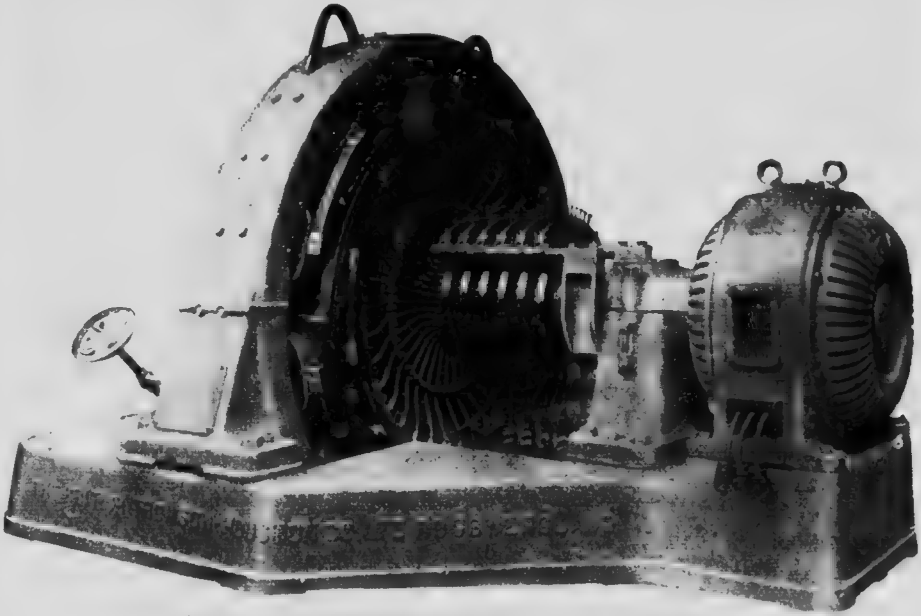

Fig. 1,001.—The Alternate-current Side of a 1,000-kw. B.T.H. Rotary.

It is a six-phase, twelve-pole machine, and therefore, when supplied with alternate currents of 50 periods per second, will run at a synchronous speed of 500 R.P.M. The alternate-current end of the machine is shown in Fig. 1,001, in which the six slip rings, with their brush gear, are prominent. The supply of six-phase currents necessitates three equally spaced connectors from the slip rings to the armature for each pole span of the field; these radial connectors can also be very clearly made out in the figure. The substantial end bearing and pedestal should be noted, the latter being designed to contain a good reserve of lubricating oil to ensure cool running for long periods. The depth gauge to indicate the level of the oil can be seen at the side. Ring-lubrication is employed, and the bearings are self-aligning. It may further be noted that the necessity of providing substantial slip rings and brush mountings has considerably increased the over-all length of the shaft and bed-plate, and that the bed-plate casting has been designed so as to form a small platform from which the brush gear and rings can be readily inspected whilst the machine is running.

The continuous-current end of the machine is shown in Fig. 1,002. Viewed from this end, the machine appears as a substantially-built continuous-current dynamo, very similar to some of the machines which have been illustrated in the chapter on dynamos. It may be noted that the brush mounting, which is supported from the yoke, is exceptionally massive and rigid, the latter being a point of great importance in the design of rotaries. Both the brush yoke and the +ve and —ve bus rings are divided along a horizontal diameter, so that the whole of the brush gear may be removed without disturbing the brush spacing. A hand-wheel for rotating the brush gear is also shown; but this is only required for the first adjustment of the brush position, which, when once set, need not be changed, but will be correct for all loads. The small terminal

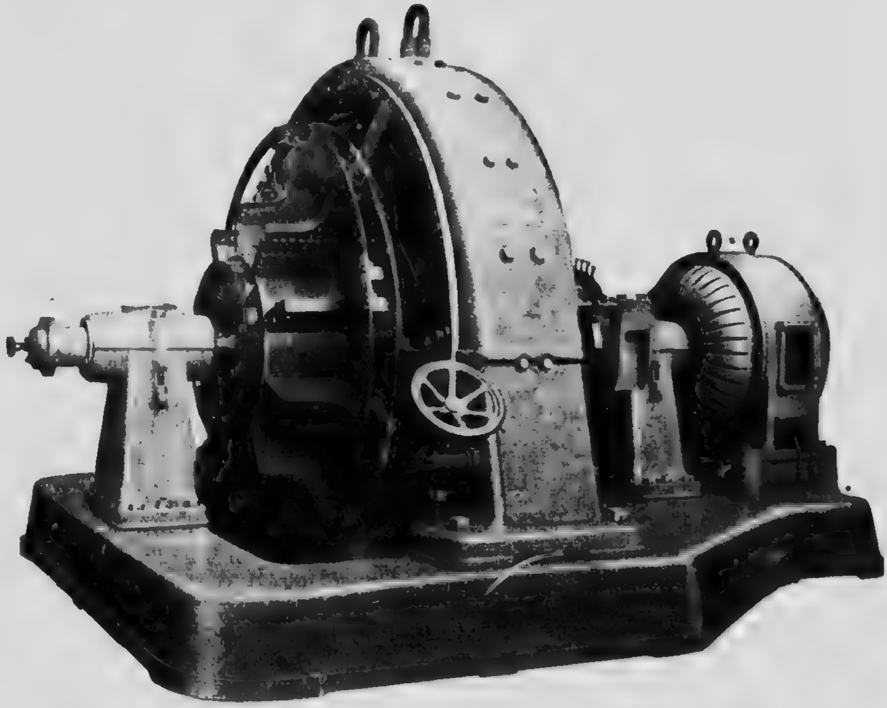

Fig. 1,002.—The Continuous-current Side of a 1,000-kw. B.T.-H. Rotary.

board on the yoke is a field reversing switch to which allusion is made later.

A large British Westinghouse rotary converter, having a capacity of 1,800 kilowatts, is shown in Fig. 1,003, in which, being a side view, details of both ends of the machine can be made out. The set has 10 poles, is designed to run at 250 R.P.M. on a 25-period circuit, and to deliver currents at 440 to 520 volts from the continuous-current brushes; at the highest voltage the full-load current will therefore be nearly 3,500 amperes, necessitating the heavy brush gear shown. In this case there are two additions to the complete set which did not appear in the set previously described. In the first place, at the alternate-current end of the machine a starting motor is mounted on a bracket which projects beyond the end bearing. This is an induction motor used for the purpose of starting the large machine from the alternate-current supply mains; details of its connections and operation are given later. The other addition is the insertion of an alternate-current booster between the slip rings and the armature for the purpose of regulating the voltage at heavy loads. The yoke of the booster is supported by brackets projecting axially outwards and radially inwards from the field yoke of the large machine. The operation of this booster is also explained later.

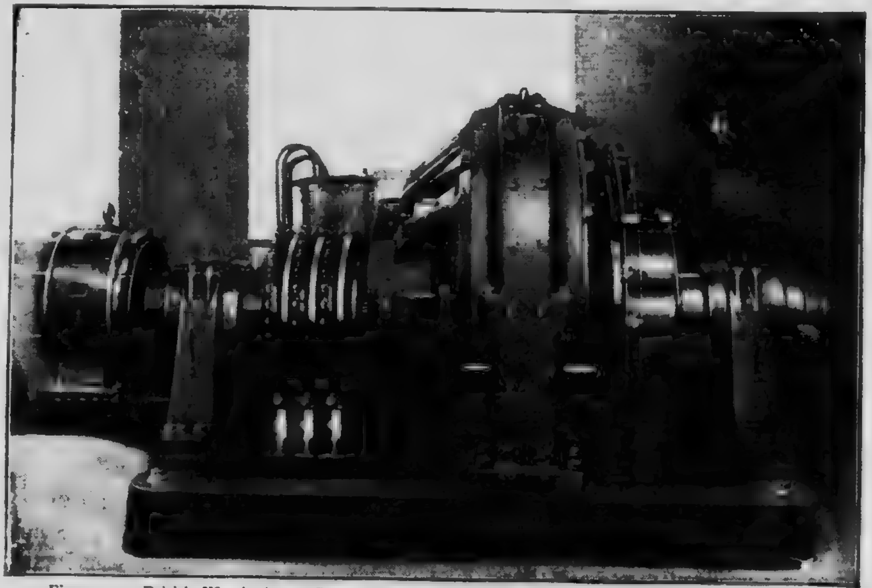

Fig. 1,003.—British Westinghouse Rotary Converter, 1,800 kw., 250 R.P.M., with A.C. Booster and Starting Motor

III.—ROTARIES: SOME DETAILS OF CONSTRUCTION

Both as regards the alternate-current and the continuous-current end, as well as the details of the armature and field magnets, the design of rotaries follows somewhat closely the design of corresponding parts on alternators and dynamos, and these parts have been fully described and illustrated in preceding chapters. Practically the underlying principles are the same, but there are some differences in detail which are worthy of passing reference.

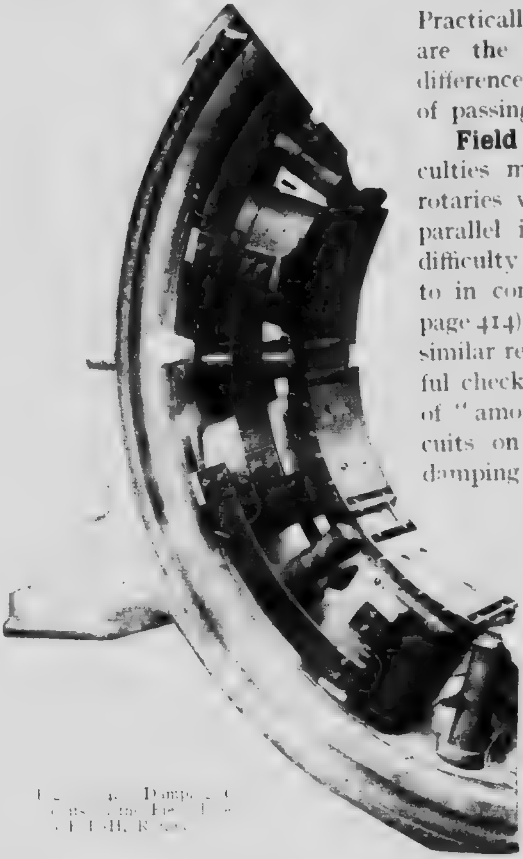

Fig. 1,004.—Damping [illegible] Field [illegible] B.T.-H. R[illegible]

Field Poles.—One of the difficulties met with in the working of rotaries when several are running in parallel is a tendency to "hunt," a difficulty we have previously referred to in connection with alternators (*see* page 414). As with alternators, and for similar reasons, one of the most powerful checks on this tendency is the use of "amortisseur" or "damping" circuits on the field pole shoes. Such damping circuits or "copper bridges," as they are sometimes called, are shown in Fig. 1,004, which represents a portion of a field ring of a British Thomson-Houston rotary. The pole face is pierced transversely with four holes, in which drawn copper rods are inserted, whose ends are expanded into holes in a heavy copper casting which surrounds the pole face. No bolts or nuts are used, and the whole forms a copper grid of low-resistance damping circuits, whose action is very effective. The particular frame illustrated in Fig. 1,004 is part of a 750-kilowatt rotary; the interpoles and other details may also be noted.

Damping grids of copper are still more apparent in Fig. 1,005, which represents the field magnet system of a British Westinghouse rotary. In this case the pole face itself is slotted to receive the intermediate copper bars which are riveted to the sides of the outer rectangle. These diagrams should be compared with Figs. 433 and 434, in which are given details of similar "dampers" for large alternators.

In both these cases the details of the interpoles should be noticed, and also the details of the conducting straps used for carrying the exciting currents from coil to coil. Fig. 1,004 shows the shunt connectors and Fig. 1,005 those for the interpole field, the connectors for the other field being in each case on the other side.

Armatures, Commutators, and Slip Rings.—It is not necessary to give at length further details of construction for rotaries, in addition to those already supplied for dynamos. If possible, greater care should be given to details of insulation, such as slot linings, etc., in view of the alternating character of the mechanical strains to which the conductors are liable in lieu of the strains in a specific direction which are met with in dynamos and motors. Substantial construction is as necessary in one case as in the other, and also an absolutely rigid connection between the armature and the commutator spiders. One illustration of an armature is given in Fig. 1,006, which depicts a British Westinghouse armature as seen from the alternate-current end. In these days, when large modern alternators are invariably of the revolving field type, with fixed armatures, it gives details of the one point in which a rotary differs from such an alternator, namely in having a revolving armature, and in the necessity of providing slip rings more complicated in character than those which are necessary for revolving field magnets. In this case the slip rings are of bronze, and are shrunk on to a cast-iron bush keyed to the shaft, the slip rings and bush being insulated from one another by a mica cylinder. The open character of the disc part of the ring should be noted; this fulfils two objects—it

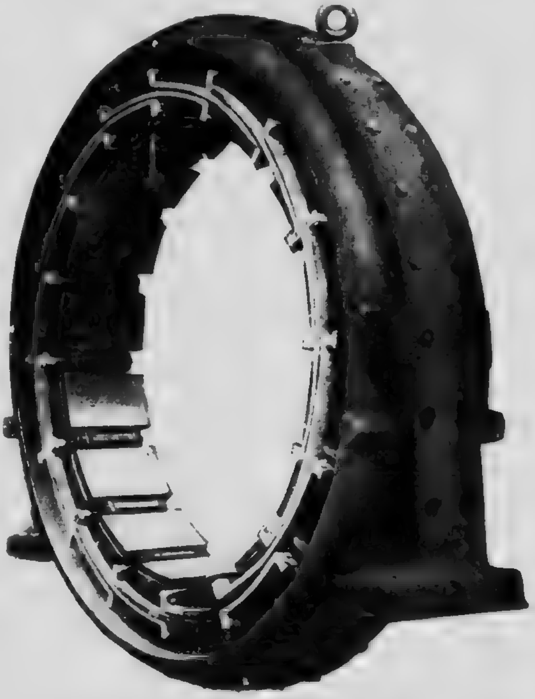

Fig. [illegible].—Damping Grids on the Field Magnets of a British Westinghouse Rotary.

promotes ventilation, and also provides spaces for the horizontal connectors to the radial conductors passing to the armature windings.

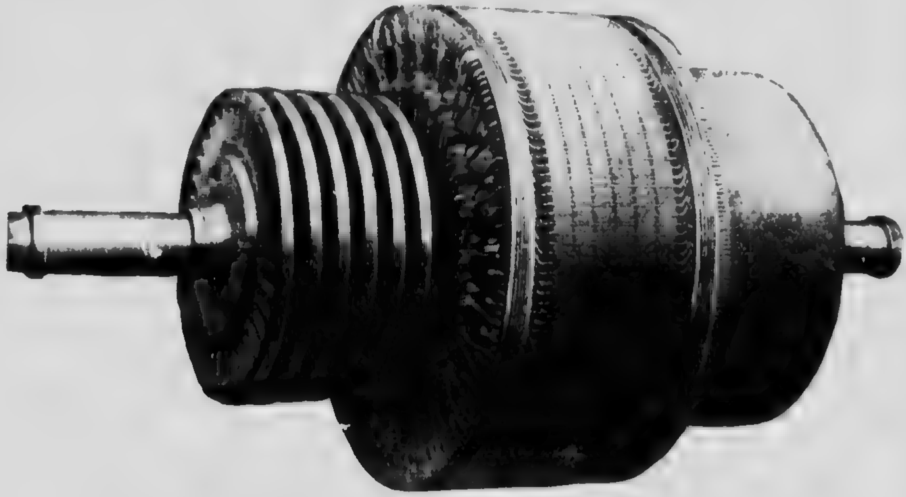

Fig. 1,006.—Armature with Slip Rings and Commutator of a British Westinghouse Rotary.

As an additional example of slip-ring construction Fig. 1,007 shows the slip rings of a British Thomson-Houston 750-kilowatt rotary converter. The support in this case is a cast-iron sleeve, upon which a mica sleeve has been compressed and ground to size. On this the slip rings are shrunk, no bolted connections which are liable to become loose being used. The slip rings are specially perforated so as to propel a good draught of air under their outer surfaces, thus conducing to cool running. The bolt connections to the various rings are well insulated with mica tubes throughout their length.

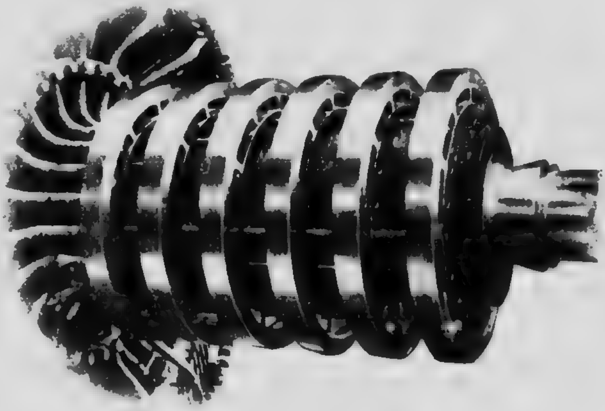

Fig. 1,007.—Slip Rings of a 750-*kw.* B.T.-H. Rotary.

Comparison may be made between the above details of slip rings and their mounting for rotaries with Fig. 375, in which the slip rings for the field magnets of an alternator are shown.

Continuous-current Brush Gear. Here, again, good generator practice is followed; but, as remarked above, in rotary converters, and especially in those which have to be placed on high-frequency circuits, very rigid construction is essential. Except, therefore, in small machines, the brush gear should not be supported from the pedestal, but either from the magnet yoke or from the base. Examples of the former of such supports being used have already been given (*see* Figs. 1,002 and 1,003). In Fig. 1,008 we give an example of a machine in which the brush gear is supported from the base plate. The machine, built by Siemens Brothers Dynamo Works, is a 1,500-*k*W. rotary, 16 ft. long by 9 ft. wide by 9 ft. 6 in. high from floor level; it is a 14-pole machine, and therefore runs at 428 R.P.M. on a 50-period circuit. The details of the brush mountings may be usefully compared with those of the dynamos of the same makers illustrated in Figs. 9 and 166.

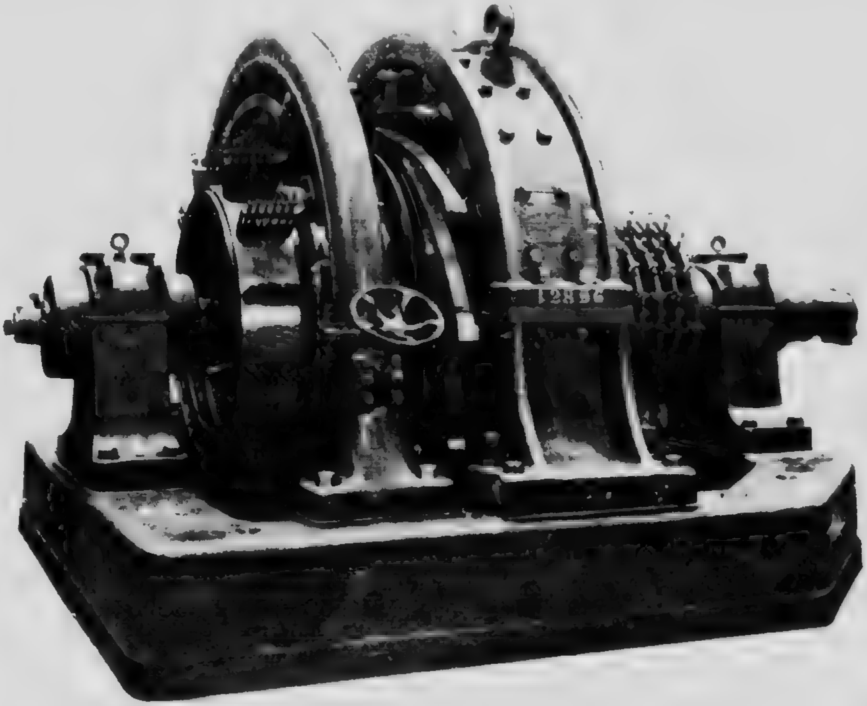

Fig. 1,008.—A Siemens Rotary Converter showing Continuous-current Brush Gear.

Alternate-current Brush Holders and Brushes.—The continuous-current brush holders and brushes follow good modern practice in continuous-current generator design; but, as pointed out above, the alternate-current gear of this kind necessarily differs somewhat from the simpler gear, which is all that is required on modern alternators.

The brush mounting on a British Westinghouse rotary converter is shown in Fig. 1,009. The bracket for supporting the brush arms is mounted on the bearing housing; but in the larger machine depicted in Fig. 1,003 it is mounted on the bed-plate. In large machines the brush arms are circular and encircle the slip rings, being insulated from the bracket; the brush holders, which are of the box type, are attached at intervals to these arms. In smaller machines the brush arm is screwed into the bracket and insulated from the brush holder.

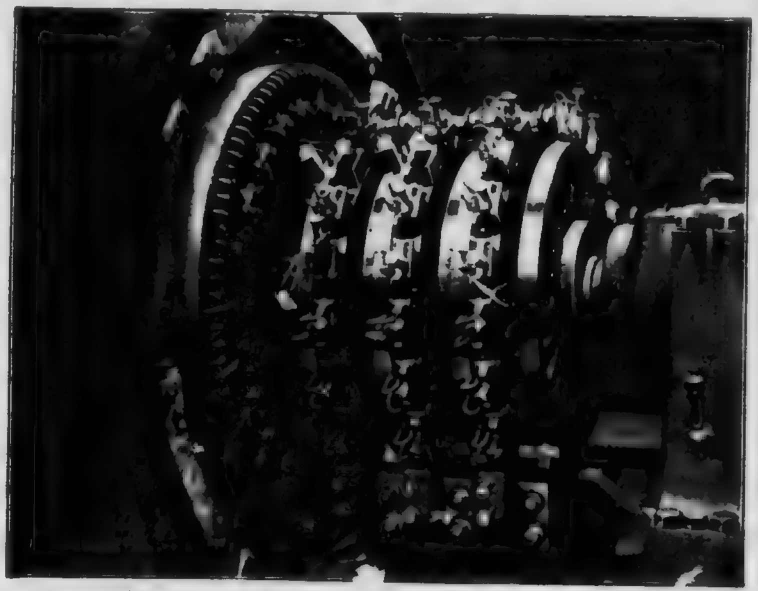

Fig. 1,009.—A.C. Brush Gear of a British Westinghouse Rotary.

The brush holders and brushes used by the British Thomson-Houston Company are shown in Figs. 1,010 and 1,011, the former being the brush gear used on small machines, and the latter that placed upon large rotaries. Carbon brushes are used, and the same considerations apply to the design of brushes and holders as those which have been set forth elsewhere (*see* pages 146 *et seq.*). In

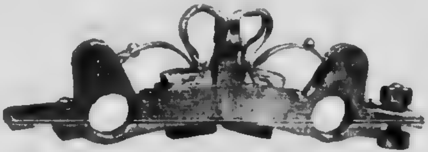

Fig. 1,010.—B.T.-H. A.C. Brush Gear for Small Rotaries.

Fig. 1,010 the necessary pressure is applied by flat curved springs, and in Fig. 1,011 by coiled spiral springs; in both cases the pressure can be adjusted. Multiple brushes are used for obvious reasons, both here and in the Westinghouse design. A feature of this design is that the whole of the brush gear is mounted on the top of the slip rings; this makes the gear accessible, and avoids the accumulation of dust on the upturned faces of under mounted brushes. In Fig. 1,011 the top of the brush holder can be flung back, giving access to the brushes for cleaning and replacement. A 500-kilowatt machine with the brush gear so thrown back is shown in Fig. 1,012. It should be noted that in this machine the brush gear is supported by two pedestals standing on the base plate of the machine, and in this respect it differs

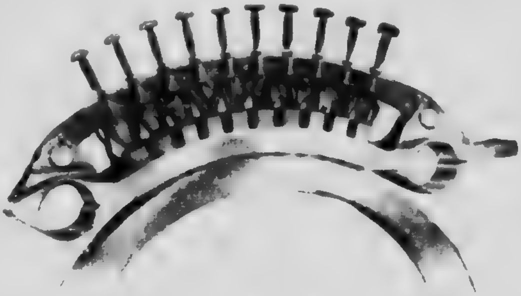

Fig. 1,011.—B.T.H. [illegible]

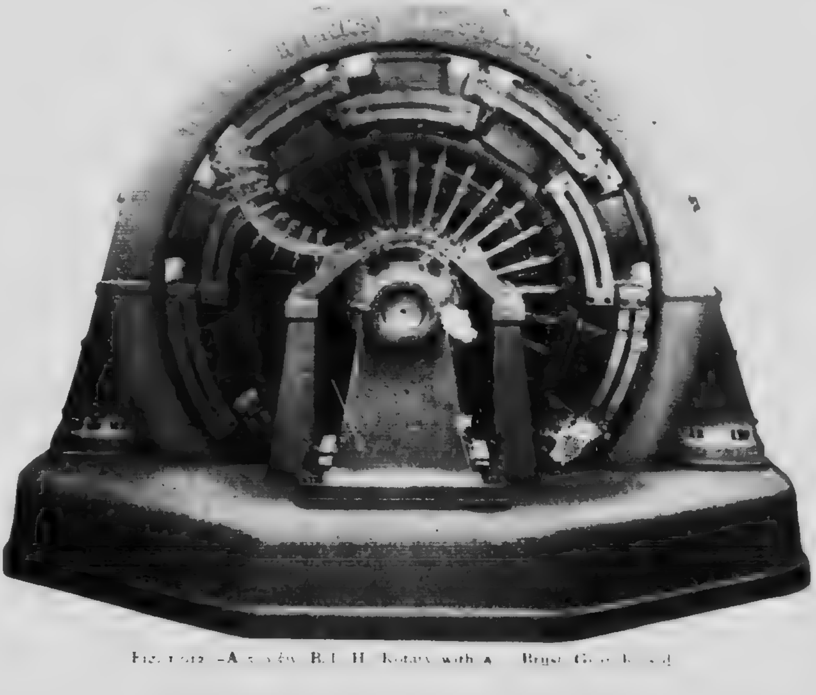

Fig. 1,012.—A 500-kw. B.T.H. Rotary with A.C. Brush Gear Thrown Back.

from the machine of twice the output built by the same makers and shown in Fig. 1,001. There are other differences between the two machines which may be noted by the reader

IV.—NOTES ON THE ELEMENTARY THEORY OF ROTARY CONVERTERS AND THEIR WORKING.

In the other sections of this chapter, and in Vol. I., several interesting points in the theory of the design of rotary converters and their working have been dealt with in passing. In this section a few other points of interest are brought under consideration.

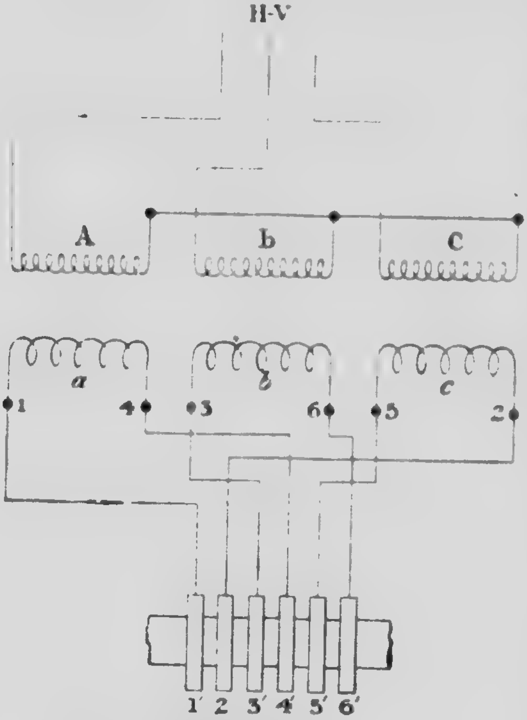

Fig. 1,013.—Connections for Six-phase Currents from a Three-phase Supply.

Current Flow and Heating. — Some of the most interesting points in connection with rotary converters arise in considering the currents actually flowing in the different conductors, in view of the fact that in normal working continuous currents are being drawn from the brushes, and when there are six slip rings alternate currents are being supplied to the armature at six equidistant points in every double-pole span.

Supply of Six-phase Currents.—As six-phase currents are not usually transmitted directly from the generating station to a sub-station, it may be of interest to show, first, how, by means of a three-phase static transformer, they can be derived from ordinary three-phase currents. In Fig. 1,013 the coils A, B, and C represent the three star-connected primaries of a static transformer receiving currents from high-voltage mains, H-V; and *a*, *b*, and *c* represent the low-voltage secondaries, quite disconnected from one another, and each with its terminals brought out and numbered as shown. It will be obvious that at any moment the potentials of the terminals 1 and 4, 3 and 6, 5 and 2 are in each pair in opposite phases, that is 180° apart (*see* page 946, *footnote*). Also that the potentials of 1, 3, and

5 are successively 120° apart. If, therefore, at a given moment 1 is at 0 in its phase, 3 will be at 120° and 5 at 240°, also 4 will be at 180°, 6 at 300° (120° + 180°), and 2 at 420° (240° + 180°), that is 60° (420° − 360°) from 1. The points in the order of the numbers, therefore, differ 60° in phase, the phases at a given moment being 0°, 60°, 120°, 180°, 240°, and 300°, and they may therefore be joined in this order to the successive slip rings 1′, 2′, 3′, 4′, 5′, and 6′ of the armature of the rotary.

Connections to Armature.—These are shown for a bipolar machine in Fig. 1,014, in which the armature is represented as a gramme ring winding inside the chain-dotted poles.* The commutator is depicted inside the armature, and still farther inwards are six concentric circles representing the six slip rings. The three secondary coils, as numbered in Fig. 1,013, are shown each diametrally connected across the gramme winding at angles 60° apart, the connection to the slip rings being indicated by dots and numbered arrows. Each coil is shown in two sections, partly to make the drawing clear, but chiefly because the central points of each coil when so joined to the windings of a rotary are all at the same potential which is half-way between the potentials of the two brushes. This is obvious when the ends of a coil are directly under the brushes; it remains true as the armature points connected to the rings rotate, for as the potential of one ring falls the potential of the other rises by exactly the same amount, and therefore the potential of the middle point remains unchanged. For this reason it is worth while bringing out leads from the middle points of the secondaries, so that after being short-circuited by the switch s they may be available for connection to the middle wire of the continuous-current three-

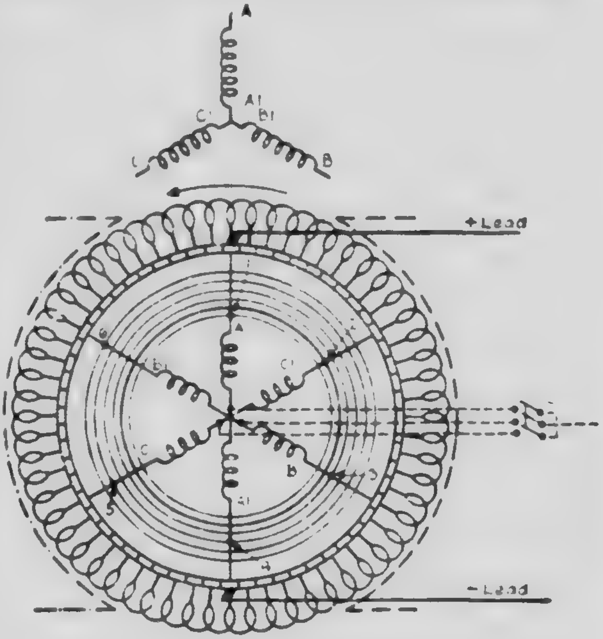

Fig. 1,014.—[illegible] Rotary Converter wire distributing circuits. The secondaries of the transformer can therefore take the place of the "static balancers" described elsewhere (*see* page 1307), as being used to regulate a continuous-current three-wire distributing system. Finally, in Fig. 1,014, the field poles, as already mentioned, are indicated by chain-dotted lines, but the excitation circuits are not shown.

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* For this illustration the Author is indebted to the courtesy of the British Thomson Houston Company.

Voltage-ratio.—One of the properties of the rotary converter, as explained elsewhere, is the approximately constant ratio between the A.C. voltage applied to the slip rings and the C.C. voltage obtained on the commutator. For a sine-wave system the voltage-ratio between the slip rings and the brushes in a simple rotary, without any regulating apparatus, as published by Dr. S. P. Thompson in 1898, has been already given for six different forms of alternate-current supply in Vol. I. (page 639). The six-phase case is included, and the table shows that when the voltage between the brushes is 100 volts the R.M.S. voltage between adjacent slip rings is 35·35 volts. The voltage across the terminals of a single transformer coil can easily be deduced from Fig. 1,014 by noting that the brushes tap the tops of the sine-waves of successive groupings of the armature conductors, and that each coil is placed diametrally across the armature. The measured R.M.S. value is therefore 100 ÷ $\sqrt{2}$, or 70·7 volts. This being so, it is further evident from Fig. 1,014 that the R.M.S. voltage between rings will be one half of this, or 35·35 volts, since two successive secondary half-coils and the armature winding between their ring ends form a mesh-connected three-phase system with the phases 60° apart.

For a three-phase supply to the slip rings the voltage between successive rings is 61·23 volts for a continuous-current P.D. of 100 volts between the brushes. In this case the connections of the secondary to the armature cannot be diametral.

Methods of regulating the voltage-ratio, so far as it is possible, are given in the next section on "Rotary Converter Working."

Currents in Armature Conductors.—The distribution of the currents in the armature conductors is complicated by the fact that the alternate-current motor currents which enter the armature windings at six definite points have superimposed upon them the continuous-current generator currents which leave and enter the windings at points which are continually changing. The current in any given conductor at a given instant will depend upon (i.) its position relative to the brushes, and (ii.) its position relative to the two nearest connections, one on either side, to the slip rings.

The problem was first worked out in detail by Dr. S. P. Thompson in the paper * mentioned above. To simplify the calculation he considered the distribution of the currents which would be set up in the armature conductors if the armature acted (i.) as a continuous-current generator only, and (ii.) as an alternate-current motor only, the distribution in the second case being worked out for different positions of the slip-ring junctions relatively to the brushes. By superimposing the two sets of currents on one another he obtained the actual distribution for each of the positions selected. Solutions were given for one-, two-, and three-phase alternate-current supply, and as both the method and the results are of great interest we reproduce the diagrams for the last-named case in Fig 1,015. On the extreme left in the top row of diagrams is the case of the bipolar generator, with an output of 100 amperes, which divides between the two available paths into two currents of 50 amperes each These currents, of course are in the same direction as the induced E.M.F.s due to the movements of the conductors in the magnetic field. The alternate-current motor currents are given for positions 15 degrees apart in the eight following diagrams on the top row. The power-factor is, for simplicity, assumed to be unity. These currents, when motor currents, flow against the induced E.M.F.s; but in a minority of cases it will be found that in some of the conductors the currents are

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* *Journal of the Institution of Electrical Engineers*, Vol. XXVII. (1898).

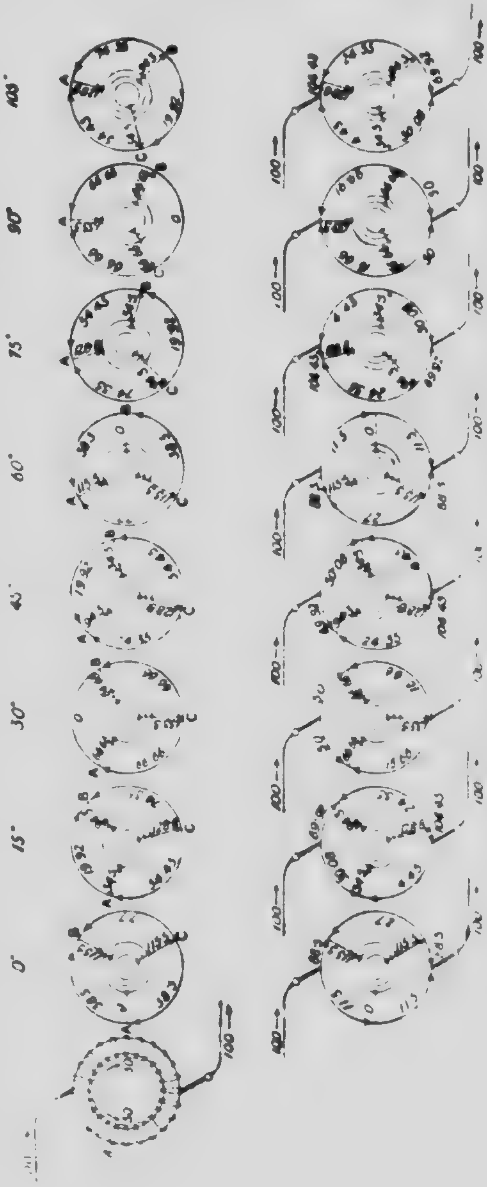


Fig. [illegible] Rotary Converter Armature flowing with the E.M.F.S, and in such cases they are generator currents bringing energy into the electric circuits. The currents follow a sine-law with a maximum value per line of 133⅓ amperes and a minimum value zero. The current from or towards any ring is a maximum when the coil connected to that ring is under a brush.

The eight diagrams in the bottom line give the results of superimposing these two sets of currents, and they should be studied carefully in detail. One or two simple points should be kept in mind, e.g. currents flowing downwards are generator currents absorbing mechanical energy from the driving core, whilst currents flowing upwards are motor currents giving energy to the core. The action is complicated, and the parts played by a particular conductor in its two functions of a current carrier, and in its mechanical actions as a motor or generator conductor, are continually changing. The gross result is that the energy is transferred from the slip rings to the brushes with a small percentage of loss due to the usual causes of electric, magnetic, and mechanical friction. In the diagrams in Fig. 1,015 these losses have been neglected, and 100 per cent. efficiency assumed.

Armature Reaction.—A further examination of the diagrams of Fig. 1,015 shows that the A.C. current between slip rings and the C.C. current between brushes have a tendency to cancel one another in the conductors with a varying effect according to the position of the particular conductor. Examined more closely, it will be found that with unity power factor the armature reaction over 180 electrical degrees due to the alternating current, balances the armature reaction due to the continuous current, thus solving automatically some of the problems of commutation.

If the A.C. power factor be not unity the cancellation of the two effects is not so perfect, and the well-known commutating troubles may develop. Simultaneously the voltage ratio is changed. For example, by over-exciting the field it is possible to boost up the C.C. voltage by as much as 5 per cent. The result, however, is that a leading current is drawn from the A.C. side, the power factor diminishes, the armature reactions are not balanced, and the efficiency of the machine is lowered. It is therefore better to obtain the increase of voltage, if required, in some other way.

On the other hand, the fact that a rotary can thus draw a leading current may be used with advantage to counteract the effect of lagging currents in other parts of the supply system, and in this way raise the efficiency of the whole.

Efficiency —The most important of the losses is that due to heating, which depends on the mean square of the currents; and when the diagrams are examined from this point of view it is satisfactory to find that the energy so lost is less than in the case of a continuous-current generator of similar output. The calculation is not an easy one, but the result for unity power-factor, as given by Dr. Thompson in the above-quoted paper, is that the heat produced in the rotary under full load is 26 per cent. less than that produced in the continuous-current generator.

The heat losses in the copper circuits at lower power factors than unity are not quite so favourable to the rotary converter. Their values, as calculated for a three-phase rotary by Parshall and Hobart, are given in the following table:—

Power Factor	Percentage Heating
1·00	58
0·87	85
0·50	375

the comparison in each case being with a C.C. generator of the same output, and an efficiency of 100 per cent. being assumed.

On the other hand, the influence of the number of phases of the supply is very marked, and may be most strikingly shown by stating the possible output for different phases whilst the heating of the armature remains constant. The above-named writers give the following figures under conditions similar to those just named:—

Single-phase	supply,	output	0·88	of	C.C. generator
Three-phase	,,	,,	1·38	,,	,,
Four-phase	,,	,,	1·67	,,	,,
Six-phase	,,	,,	1·98	,,	,,
Twelve-phase	,,	,,	2·26	,,	,,

These figures alone, without other good reasons, might be taken to justify the six-phase supply with its cumbrous slip rings and brush gear. They also show where the motor converter scores a point over the rotary converter, inasmuch as its multiplication of phases is not hampered by the mechanical difficulty and by the cost of supplying a corresponding number of slip rings and brushes.

The efficiency of a fair-sized rotary converter as found by an actual test is given in the upper curve of Fig. 1,016, which exhibits the results of a test of a 700-*k*w. Westinghouse rotary running on a 50-period circuit and delivering continuous-current power at 500 volts. The efficiency rises to nearly 92 per cent. at quarter load and is fairly high down to one-eighth of full load. From half load up to 25 per cent. overload the efficiency rises gradually and steadily from 95·5 to 97 per cent.

In actual practice a rotary converter has to be used with a step-down static transformer, and it is therefore important to know the combined efficiency of the two transforming plants. This is given for the same rotary converter in the lower curve of Fig. 1,016, which follows closely the shape of the other curve, the differences not being very great, as would be expected in view of the high efficiency of the static transformer referred to on page 956. Thus, the efficiency of the combined set at 25 per cent. overload - that is, with an output of 875 *k*w.—is 95 per cent.

Testing.—The testing of the over-all efficiency of a rotary converter primarily involves only the electrical measurement of the A.C. input and the C.C. output, the usual precautions—which are fully described elsewhere—being adopted. A minute analysis of the separate losses is seldom required.

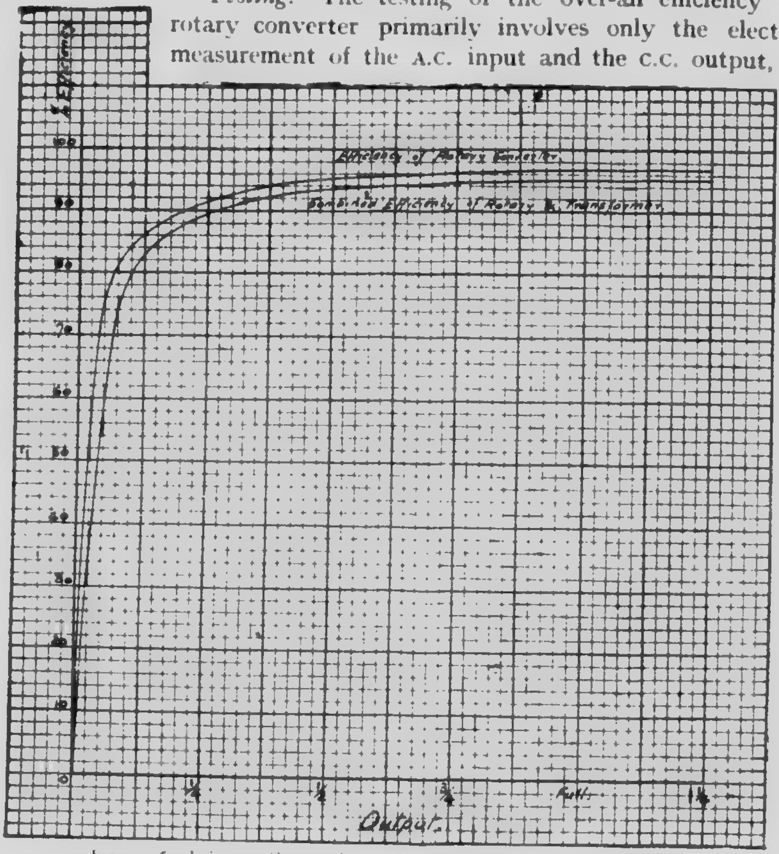


Fig. 1,016.—Efficiency Curves of a 700-*k*w. Westinghouse Rotary Converter.

A machine actually under test is shown in Fig. 1,017. It is mounted, with its starting motor, on the test plate in the works in which it has been built, in this case the Stafford workshops of Messrs. Siemens Bros. Dynamo Works, Limited. The machine is a six-phase rotary converter, having an output at full load of 2,000 *k*w. at 250 R.P.M. on the continuous-current side when supplied with alternating currents at 25 periods. It is a 12-

pole machine, and is 13 ft. 6 in. long by 13 ft. 6 in. wide by 17 ft. high from floor level. The figure also shows the necessary step-down transformers with their high- and low-voltage terminals and carrying the expansion tanks for the oil supply already described on page 923, and illustrated diagrammatically in Fig. 945. The table and board carrying the testing instruments are shown on the left-hand side.

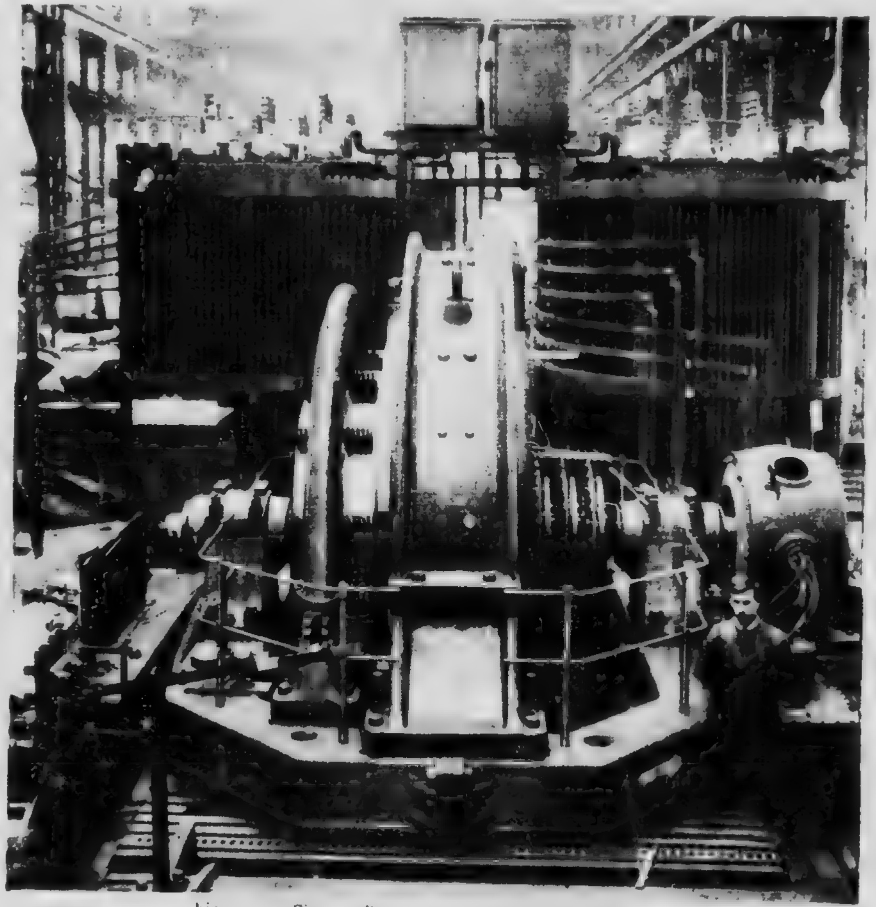


Fig. 1,017.—Siemens Rotary Converter under Test in Works

V.—ROTARY CONVERTER WORKING

The problems presenting themselves in the operation of rotary converters, though in some measure of the same general kind as those which arise in the working of other electrical machinery of similar type, develop certain interesting points which are peculiar to the special conditions. Some of these problems have been touched upon in the preceding section. Other than those connected with the running of any machines, they may be broadly divided into two classes, namely: (i.) the starting of the machine, and (ii.) the regulation of the voltage of its output.

Before, however, dealing with these matters, it should be premised that by far the largest sphere for the use of rotary converters at present is to convert high-voltage alternate-current power to comparatively low-voltage continuous-current power. This is due to the fact, elsewhere explained, that for long-distance power transmission high-voltage alternate currents have been found to be the most economical. On the other hand, comparatively low-voltage continuous-current electrical power is by far the more convenient for many purposes in the ultimate applications of electricity to the service of man. So much is this the case that some little time ago it was calculated that 60 per cent. of the alternate-current electrical power generated throughout the world was, before final utilisation, converted into continuous-current power. It is here that the rotary converter comes in, but because of the fixed relation between the voltages on its slip rings and the voltage on its continuous-current brushes, the complete conversion cannot be effected without the interposition of step down static transformers between the high-voltage alternate-current transmission mains and the slip rings of the rotary. This not only requires the installation of additional and costly apparatus, but also complicates the switching and regulating arrangements.

A subsidiary use of rotary converters occurs in large continuous-current generating stations in which only a small part of the power has to be transmitted to a distance beyond the limits of economical continuous-current transmission. In this case rotaries are used to transform a portion of the continuous-current power into alternate-current power, which is stepped-up to a high voltage by static transformers, transmitted to a distant sub-station, and then re-transformed into continuous-current power after the voltage has been lowered by step-down static transformers.

Starting and Paralleling.—The rotary converter, being a reversible machine, may be started from either side, provided the right kind of electrical energy is available. By far the simpler method, which will be described first, is to start up the machine from the continuous-current side; but this method is frequently inapplicable in modern practice owing to the necessary continuous-current power of proper voltage not being available.

Starting from the Continuous-current Side.—The chief precautions to be taken in starting from the continuous-current side are those, already fully set forth, for starting large continuous-current motors. There are, in this case, however, two additional points to be borne in mind: (i.) that the alternate-current main switch should not be closed until the alternate-current voltages set up in the rotary are synchronised by one of the usual methods (*see* pages 397 to 413 *ante*) with the voltages of the alternate-current supply circuit, and (ii.) that when the alternate-current main switch is closed the direction of the flow of energy has to be reversed. Up to that moment the unloaded rotary was drawing the energy required to maintain its motion from the continuous-current circuits; but on the closing of the alternate-current switch the continuous-current circuits should begin to take energy from the alternate-current circuits through the brushes on the commutator of the rotary.

It is, of course, possible, by carefully adjusting field excitation and voltages, to pass through the transition stage safely and quietly; but some engineers prefer that the continuous-current connection should be broken before the alternate-current switch is closed, and that the rotary should then be brought under load with the usual precautions. For this purpose a special switch has been designed in which the current operating the main alternate-current oil switch of a large rotary trips the continuous-current circuit breaker a fraction of a second before the oil switch closes.

The switchboard connections for starting rotaries from the continuous-current side are referred to in the chapter on sub-stations.

Starting from the Alternate current Side. The problem of starting up from the alternate-current side is more difficult, and more than one method is available; each involves special, or specially modified, apparatus, and this apparatus is usually somewhat costly and its use not free from difficulties.

The following are the chief methods which either have been, or are still, used for starting rotaries from the alternate-current side

(i.) By introducing resistance into each phase, to be removed step by step as the rotary comes up to synchronism, when the field circuits are closed.

(ii.) By using taps on the secondary of the transformer, usually interpolated between the mains and the rotary, by which a reduced voltage, increased step by step, is applied to the slip rings

(iii.) By means of a small induction motor on the shaft of the rotary, the capacity of this motor being about 7 or 8 per cent. of the full load of the rotary.

(iv.) By using a small auxiliary starting set, consisting of an induction motor and a continuous-current dynamo, the latter having an output equal to not less than 7 or 8 per cent. of the full load of the rotary. With the continuous current so obtained the large rotary is to be started up from the continuous-current side as described above.

Of these methods (i.) is cumbersome and costly, and is now practically abandoned, whilst (iv.) is only economical in a large sub-station where there are several rotaries which it is advantageous to start up one at a time, as required. Even then starting leads have to be brought from each rotary to a central point at which the current from the auxiliary set is available. As the actual method of starting the large machine with continuous current has just been described, we need not go into further details here, but proceed to consider methods (ii.) and (iii.).

Transformer Starting.—The method of starting by taps from the secondary of the transformers is, in effect, a method of starting under reduced voltage, which we have seen used for a similar purpose in other cases. One of the practical disadvantages of the method is that the transformer has to be specially constructed, which adds to its cost. Otherwise the method is a fairly simple one. The connections at the transformer are shown diagrammatically in Fig. 1,018, from which it will be seen that in practice two extra connections to each secondary of the transformer are sufficient. In this diagram the leads 1, 2, 3, 4, 5, 6 at the bottom are taken directly to the corresponding slip rings of the rotary, and in the running position are connected through to the similarly numbered ends of the secondaries, the connections to 1, 2, and 3 being direct without the intervention of the two throw-over switches X and Y, through which the starting connections to 4, 5, and 6 pass

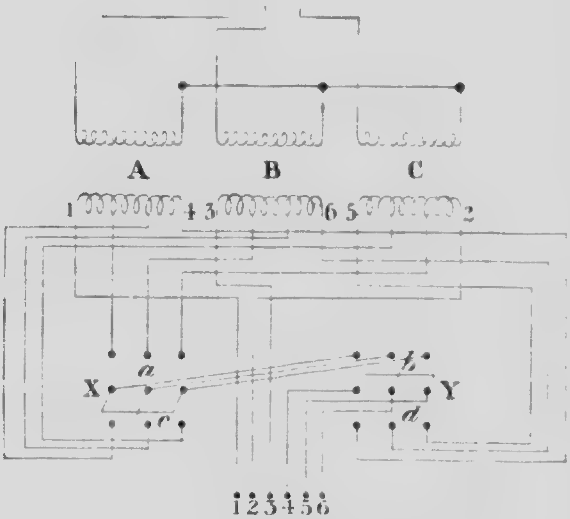


Fig. 1,018.—Connections for Starting by Taps from Transformer Secondaries.

For starting, the switches X and Y are thrown on to the upper contacts *a* and *b* respectively, in which case the taps on the A, B, and C phases nearest to 1, 2, and 3 are joined to the slip rings 4, 5, and 6. When the rotary has started and speeded up sufficiently switch X is thrown over on to its *c*, or lower, contacts to which the second taps are joined. When the rotary has further speeded up, the switch Y is thrown on to its *d*, 10 lower, contacts, breaking connections with the taps and giving the rotary full voltage under which it comes up to speed.

In this method of starting, the rotary, whilst being brought up to speed, is acting as an induction motor, in which the armature is the primary, and the damping circuits on the field poles the secondary, or squirrel-cage, winding. The method, therefore, corresponds to the reduced voltage method (*see* page 721 *et seq.*) of starting an induction motor, and is adopted for similar reasons, in place of throwing on full voltage. With the ½ and ¾ taps shown, it is claimed that the largest current drawn from the mains during starting does not exceed half the full-load current

No synchronising is necessary, but the polarity on the continuous-current side is a matter of chance, as it depends upon the phase of the alternate current at the moment when the field switch is closed, when the rotary is running with the usual small slip of an unloaded induction motor. This polarity must, therefore, be tested, by a polarised voltmeter or otherwise, before the machine is thrown on to the continuous-current busbars. To provide for the case of it being found to be wrong, a field reversing throw-over switch is usually provided, and is often fixed on the yoke of the machines. The successful manipulation of this switch, however, requires care and not a little practice. A little consideration will show that a mere reversal of the connections between the field terminals and the brush terminals will not do, inasmuch as the direction of rotation of the machine remains as before, and a reversal of field therefore results in a reversal of brush polarity, and therefore a re-reversal of field if the switch remains over. What is really necessary is that the rotating armature should *slip a pole*, for it must be remembered that when rotating at synchronous speed the magnetic field of the rotating armature of an alternate-current generator or motor is *fixed in space* (*see* page 304). One method of manipulation is, therefore, to open the field switch and hold it open for a moment, so that the armature may begin to slip, then close it in the crossed position before the brushes have quite lost the wrong polarity, but only hold it closed for a moment; then open it again, keep it hanging open for another moment, and finally close in the original or running position.

Another way of getting over the difficulty in which field connections are not reversed is to place a polarised voltmeter across the brushes with the field switch open. When the rotary is approaching synchronism the voltmeter needle oscillates, at first quickly and then more slowly, on both sides of the zero. When the slowly moving needle is well over on the right side the field switch is closed and the field then built with the correct polarity. Supposing, however, that the polarity becomes reversed, the field switch should be opened to allow the armature to "slip a pole" and then closed. But if the brush voltmeter does not indicate the correct polarity, the switch E (Fig. 1,021) should be opened for a moment, throwing the rotary out of step. On reclosing the field switch, synchronism is again obtained, and if the moment of reclosing has been properly chosen the polarity will now be correct. Some practice is required to be successful with this method.

The continuous-current load, it should be repeated, should never be put on until the polarity of the brushes after starting up has been tested.

Induction Motor Starting.—This method primarily involves the usual precautions, which have been discussed elsewhere, of starting an induction motor under load, the load in this case being caused by the inertia of the rotary armature. A squirrel-cage induction motor is the most convenient, the danger in using it being disturbances in the alternate-current circuits due to possible large starting currents. If the full load of the rotary is only a small fraction of the load on the generating station the disturbance will not be serious, but if the rotary be the chief part of the load further precautions may be necessary, and a wound induction motor with slip rings and starting resistances must be used.

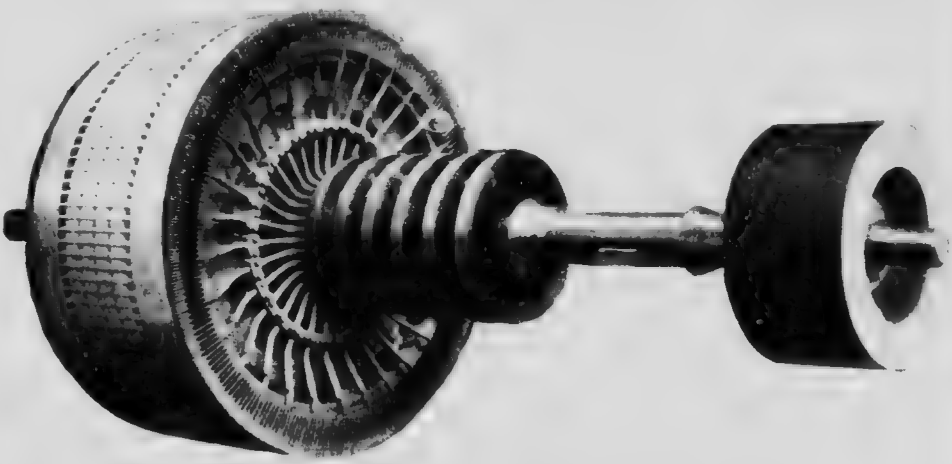


Fig. 1,019.—Solid Rotor of Starting Motor on Shaft of Armature of 750 K.W. B.T.H. Rotary

This method of starting was referred to in the historical section (Vol. I., pages 639 to 641), and an illustration (Fig. 618), taken from an early type of machine, was given of the squirrel-cage rotor of the starter on the shaft of the armature of the rotary. The rotors of the starting motors, though only used occasionally, have to work under somewhat severe conditions, and should therefore be strong and of simple design. Experience has thus led to a revival of the simplest and strongest design possible, used in some very early forms of induction motors, namely, a cylinder of cast metal suitably mounted on the shaft. Such a rotor on the shaft of a

750-*kw.* rotary is shown in Fig. 1,019, which also exhibits the complete armature of the rotary. The illustration is taken from a British Thomson-Houston machine. Such a rotor should be indestructible.

If the induction motor used has a smaller number of poles than the rotary its synchronous speed will be higher than that of the rotary, and it is possible to obtain a slip speed from it equal to or greater than the synchronous speed of the rotary. To adjust the slip a small resistance may be inserted in one of the motor leads.

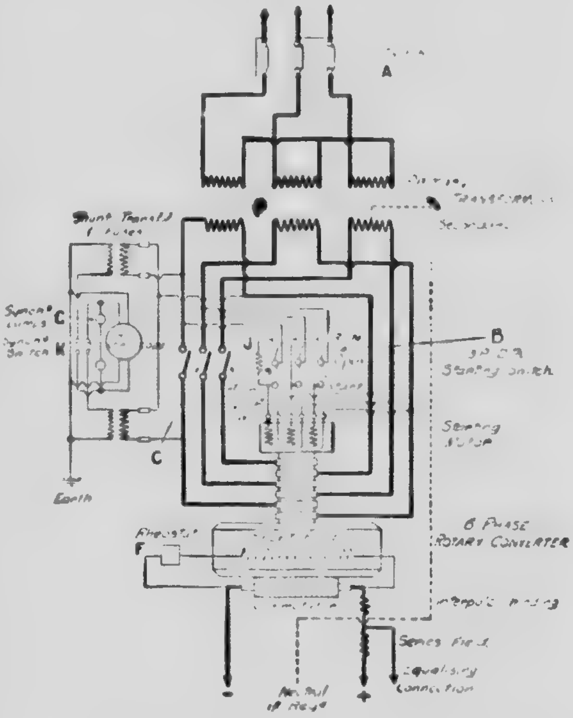


Fig. 1,020.—Induction Motor Starting. Synchronising necessary.

Synchronisation is necessary in this method, and will ensure that the continuous-current polarity comes up correctly. If the starting motor is being run up from the main transformers the synchronising can be done between two diametral rings (say 1 and 4 of Fig. 1,013) on the rotary and the terminals of the transformer. This will be clear from an examination of Fig. 1,020, for which the author is indebted to the British Westinghouse Co., and in which the synchroscope connections are given. The starting switch B for the induction motor has two positions, namely starting and running, and in the latter an adjustable resistance J is in one of the phases. When synchronism is attained the main switch C is closed, and the starting and synchronising switches B and K should then be opened. The field rheostat F is next adjusted until the proper continuous-current voltage is obtained, and the load can then be taken over by further adjusting the rheostat.

In Fig. 1,020 it will be noticed that three of the slip rings are connected to the transformer terminals during the starting operations, and one of these connections is made use of for synchronising. In the Westinghouse *self-synchronising* method the remaining three slip rings are also joined up to the transformer terminals, but with the stator coils of the induction motor interposed. This method is diagrammatically shown in Fig. 1,021, in which, with switch C open and switch B closed, the connections are as just described. The rotor of the induction motor, which is of the squirrel-cage type, is not shown. When switch B is first closed the starting motor has practically full voltage across its coils because of the low impedance of the armature coils in series with them; but the current drawn from the mains need not, with machines having eight or more poles, exceed 30 per cent. of full-load current, and this is insufficient to affect the polarity of the magnetic circuits of the rotary. With six-pole machines the starting current may rise to 50 per cent. of the full-load current, and to deal with these cases the single-pole field switch E is provided. The switch B is not necessary, though it is desirable.

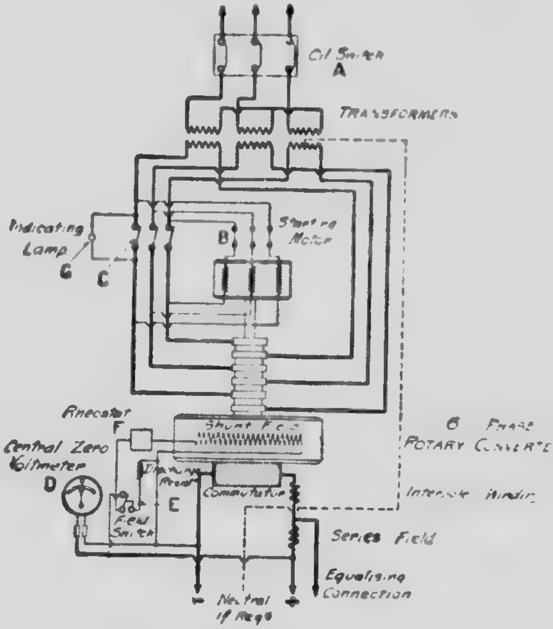
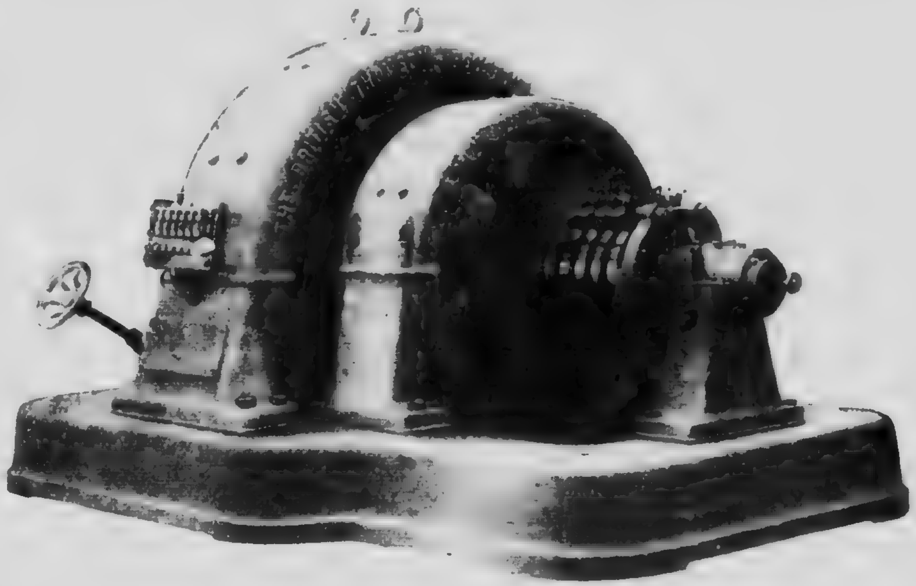


Fig. 1,021.—Westinghouse Self-synchronising Method of Induction Motor Starting

On starting, the field rheostat F being set to the position for normal voltage, the high-voltage oil switch A is closed, all other switches being open except E in the case of large machines. On closing B, or even in its absence, the rotary starts at once and runs up to speed. When the continuous-current voltage begins to build up, the polarised voltmeter D is watched, and the field current is adjusted to give normal voltage or slightly less. The switch C is then closed, short-circuiting the coils of the stator of the induction motor, and the switch B is opened or not as the case may be. The closing of C causes no rush of current, as the rotary is running in synchronism with its field adjusted. The machine is then ready to be paralleled with other machines in the usual way.

Of the three methods described, the last is the simplest, because no synchronising apparatus is required; the switching apparatus is simple and the starting operations few. Moreover, the starting polarity comes up right, and the line starting current is small; in addition, there is no sparking at the brushes. There is, however, the starting induction motor, which adds to the cost as compared with the [illegible] method. This latter method has the disadvantage of [illegible] starting currents, which have the further disadvantage that the circuit breakers must be set to open with a higher current than is desirable, with a consequent limitation of their capacity to protect the machine.

Voltage Regulation. As explained [illegible] the [illegible] peculiarities, and, in fact, disadvantages of the rotary converter [illegible] the practically fixed ratio which exists between the voltage on the slip rings and the potential difference of the continuous current output. There are,



[illegible]

however, methods by which the ratio can be varied within certain limits, which are very narrow when compared with the wide variations of alternate current voltage obtainable with static transformers.

The principal methods by which such variations of the voltage ratio between the slip rings and the brushes, and the wider voltage ratio between the high-voltage supply terminals and the brushes, can be effected may be summarised as follows:

(i.) By the insertion of an alternate-current **booster** between the slip rings and the armature of the rotary.

(ii.) By altering the distribution of the **field flux** in [illegible] of the methods of doing this being to use a **split pole**.

(iii.) By altering the position of the **brushes** on the [illegible] (iv.) By inserting an **induction regulator** between the transformer and the slip rings.

(v.) By introducing **reactance** between the transformer and the slip rings or into the transformer itself.

(i.) *Booster Regulation.*—The first method is one of the oldest devised for dealing with the problem, it having been used in the Alioth "Commutatrice Survolteuse" in 1896, long before the modern rotary was developed. In modern machines the booster, which is naturally smaller than the main machine, is mounted on the bed-plate of the rotary and is, in fact, a small alternator with fixed fields, having the same number of poles as the rotary, and therefore at synchronous speed generating currents of the periodicity of the supply circuits. An example has already been given in Fig. 1,003.

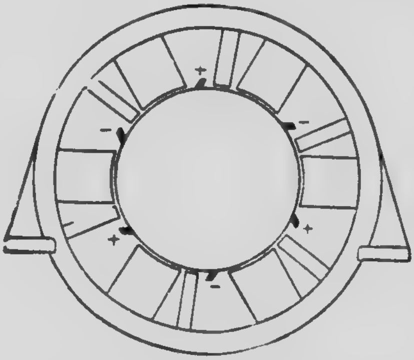


Fig. 1,023.—Split-pole Magnet Frame.

Another example of the combined plant is given in Fig. 1,022, which depicts a standard rotary converter set built by the British Thomson-Houston Company. The set is designed to give an output of 250 kilowatts on the continuous-current side; and since both the rotary and the booster have each six poles, the synchronous speed is 500 R.P.M. when running on a 25-period supply circuit. The armature of the booster is wound like an ordinary continuous-current drum armature, with points 60 electrical degrees apart connected to the slip rings. The field magnets are separately excited, and by altering the excitation, and even reversing it, the alternate-current voltage delivered to the armature of the rotary, and therefore the continuous-current voltage on the brushes, can be either raised or lowered within the limits of the corresponding voltage generated by the booster. The control is therefore exercised through the field magnet circuit of the booster.

The power-factor of the set is not affected by load or voltage when booster control is employed, and therefore it is possible to run with unity power-factor, or even with a leading current, in which case the set will act as a *phase-advancer.*

From the point of view of voltage regulation the method is highly successful; but it has the great disadvantages that it increases the capital cost of the rotary, and necessarily lowers the efficiency of the whole machine.

(ii.) *Flux or Split-pole Regulation.*—The second method of altering the voltage ratio between the slip rings and the brushes by altering the distribution of the field in the gap was also early recognised as one by which some slight variations might be effected. In modern rotaries it is applied very drastically by the use of a *split pole*, which is shown diagrammatically in Fig. 1,023, in which the iron carcass of a machine so regulated is depicted. The field is a six-pole field, but the core of each pole is in two parts—the main core and an auxiliary core. By exciting the latter separately it can be given any strength, + or −, relatively to the main flux, and the continuous-current voltage will depend upon the *arithmetic* sum of the fluxes over any complete polar span. The voltages between the slip rings, however, depend (apart from current retardation drop) upon the *vector* sum of the E.M.F.s in the armature conductors, the magnitude of the vector of any particular conductor depending upon the flux it is cutting at the moment, and its vectorial angle depending on its position in the polar gap. If we were dealing with single-phase currents (two slip rings) the relative effects would be as shown in the vector diagram of Fig. 1,024, in which it is assumed that the maximum flux of the main pole is six times that of the auxiliary pole. In the diagram OM represents the flux of the main pole and Mm that of the auxiliary, the E.M.F.s in the conductors being proportional to these fluxes. For the continuous-current brushes (current retardation drops being neglected) the effect of exciting the auxiliary pole to its maximum is to give a potential difference corresponding to the flux represented by either Om_1 or Om_2, according as the auxiliary flux is + or −. For the alternate-current slip rings, with the auxiliary pole, as in Fig. 1,022, 70 degrees (electrical) from the main pole, the E.M.F. caused thereby is either Mm' or Mm, according as the excitation is + or −. The maximum E.M.F. between the slip rings will therefore be Om' in the one case and Om in the other, and the difference between these is much less than the difference between Om_1 and Om_2. If the angle m_2Mm were nearer 90 degrees, the alternate-current difference would be less. This proves that a much greater effect can be produced on the continuous-current side than on the alternate-current side, and that with the alternate-current voltage held constant the continuous-current voltage can be varied through an appreciable amount. The measured voltage of the slip rings would be calculated from Om or Om', divided by $\sqrt{2}$ for a sine-wave law.

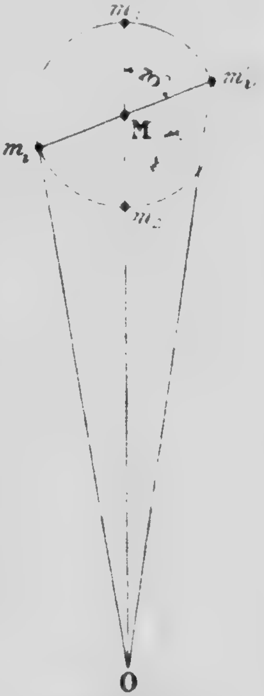


Fig. 1,024.—Split-pole Vector Diagram [illegible] phase Working.

The analysis for a six-phase supply is more complicated; but the general result is the same, and is proved to be correct by actual measurements of the voltages.

An actual field-magnet with its poles so divided, and also provided with commutating poles, is shown in Fig. 1,025. The magnet is shown fully wound, and the figure also shows very clearly the damping grids on the main pole faces. The details of the connections of the coils are of interest. The illustration is taken from a 250-*k*w. four-pole machine built by the British Thomson-Houston Company to run at 750 R.P.M. on 25-period circuits.

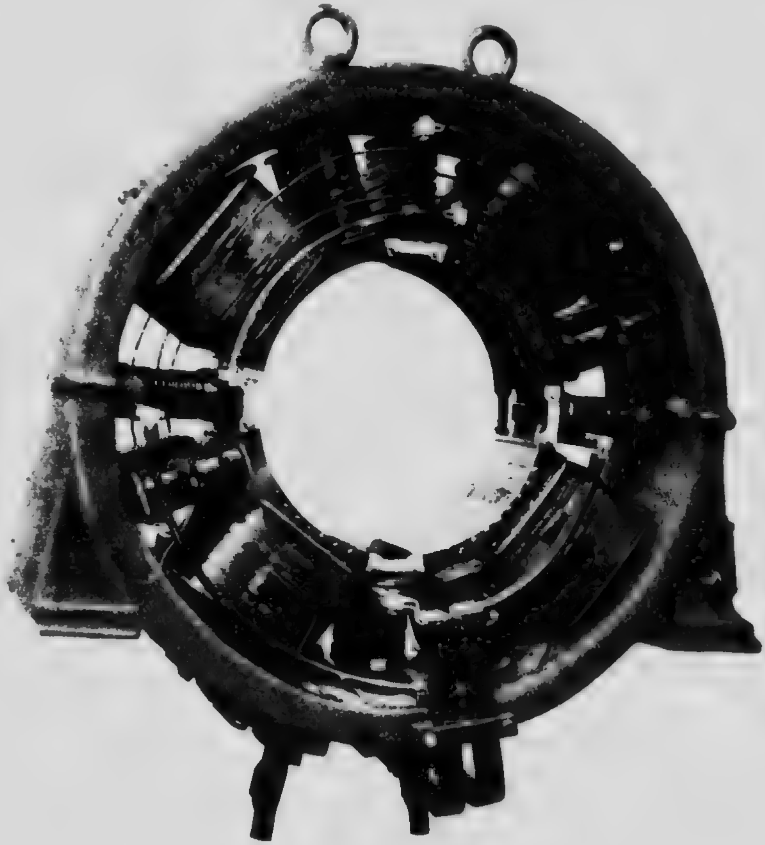


Fig. 1,025.—Field Magnets of 250-*k*w. Split-pole B.T.-H. Rotary with Commutating Poles.

It is claimed by the British Thomson-Houston Company that the field can be so designed that the sine-wave condition is fulfilled, and that, therefore, higher harmonics which might cause disturbances are not introduced. Unity power-factor can also be easily secured.

On the other hand, the method leads to commutating and other difficulties if applied to large rotaries and on high-frequency circuits. It appears so far only to have been applied to rotaries up to 250-*k*w. and to frequencies not exceeding 25 periods. In these cases a 25 per cent. voltage variation has been attained successfully without the use of a booster.

(iii.) *Brush-shifting Regulation.*—On the continuous-current side the maximum potential difference between the brushes is obtained when the brushes are in the neutral position, and the potential difference falls when the brushes are rocked from this position. From what has been said in previous chapters it will be understood that if the brushes are rocked very far from the neutral positions, so as to obtain a substantially lower potential difference, difficulties of commutation will be encountered, and that for a forward lead on light loads, if the brushes are under the main pole tip, there will be heavy circulating currents which will give trouble, even though the sparking may not be serious. It is well, therefore, not to depend on this method if a serious alteration of potential difference is desired.

(iv.) *Induction Regulation.*—This method of regulation consists in inserting between the step-down transformer and the slip rings an *induction regulator*, such as is described in the chapter on the static transformer. Such a regulator, which is a variable [illegible] static transformer with a secondary which can be set in different positions, can either raise or depress the voltage of the leads on which it is placed. For instance, it can be designed to alter the voltage up or down over a range of 10 per cent. in either direction, that is 20 per cent. in all. It acts upon each phase separately and, as may be gathered from the description of the three-phase regulator on page 1302, it is a complicated and costly piece of apparatus when it has to deal with six phases instead of three. In fact, for the same range of regulation, it costs more than a booster in a given case, and therefore the latter is usually preferred. Its use, like that of the booster, leaves the power-factor independent of load and voltage.

(v.) *Reactance Regulation.*—This method, which introduces reactances or choking coils on the alternate-current side, was also early recognised as a method by which the voltage of a rotary could be regulated.

As explained elsewhere (*see* page 990), the power-factor of the alternate-current power received from constant voltage alternate-current mains by a rotary converter depends on its field excitation. With a certain excitation the power-factor is unity ($\phi = 0$), and the current is in phase with the voltage. If the field be weakened below this value the current absorbed by the rotary is a lagging current, whereas if the field be strengthened the current is a leading current. In the former case reactance in either of the positions indicated above (*see* (v.) page 1002) will lower the voltage at the slip rings, and in the latter case will raise it, and the continuous-current voltage will follow these changes.

The simple vector diagrams in Figs. 1,026 to 1,028, published by the British Thomson-Houston Company, show how the changes in the phase of the current lead to these results. In each diagram the vector O P of constant length represents the constant voltage supplied by the high-voltage mains, and the vector O C represents the current, assumed constant, supplied to the slip-rings. The reactance voltage O R, drawn to an appropriate scale, is always at right angles to and lagging on O C. If now, as in Fig. 1,026, O C lags on the slip-ring voltage O S, this voltage, which is the vector sum of O R and O P, is necessarily less than O P, since the angle P O R is obtuse. The same remark applies to Fig. 1,027, where, with unity power-factor, O C and O S are in phase, but in this case the difference between O P and O S is not very great; it represents the drop in volts due to introducing a reactance into the circuit when the conditions are normal. In Fig. 1,028, O C is a leading current, and, if the lead be great enough, the angle P O R is so far reduced that O S is necessarily greater than O P. In all such cases the voltage at the slip rings is raised and the necessary regulation is obtained.

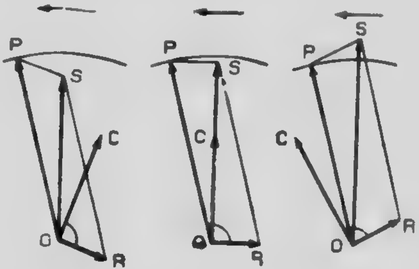


Fig. 1,026. Fig. 1,027. Fig. 1 .

Vector Diagrams of Reactance Regulation.

A method of introducing the necessary reactance, which is simpler and less costly than the provision of separate choking coils, is to design the step-down transformer with a high reactance—that is, with a greater leakage field than is usual. This involves very little increase of cost, and practically no decrease in the efficiency of the transformer.

The objection to the method is that its use involves a change of power-factor as well as a change of voltage. In commercial service, however, the high voltage is usually required when the load is heavy, and in this case the power-factor is a leading one, which may be advantageous on the whole connected system. At light loads, when the power-factor is lagging the smallness of the load tends to make it unimportant.

High-voltage Rotaries.—The demands already recorded and which are emphasised in succeeding chapters for the supply of continuous currents at higher and higher voltages have led to the close study of the problem of constructing rotaries which can safely deliver currents at 1,500 volts on the C.C. side in lieu of the 600 or 700 volts more usually offered. The main difficulty is to prevent flashing over at the brushes when short circuits or sudden changes of load occur. Very careful design of the commutating poles helps but is not sufficient because of the rapidity with which the trouble develops. In conjunction, however, with high-speed circuit-breakers operating in $\frac{1}{200}$th of a second and with special barriers and arc-quenching screens fitted on the brush spindles the necessary protection has been secured, and conversion at 1,500 volts has been successfully accomplished with large machines. Lack of space does not allow us to pursue the subject further or give details here.

Inverted Running.—It has been mentioned above (*see* page 994) that there are cases in which a rotary converter can be advantageously used

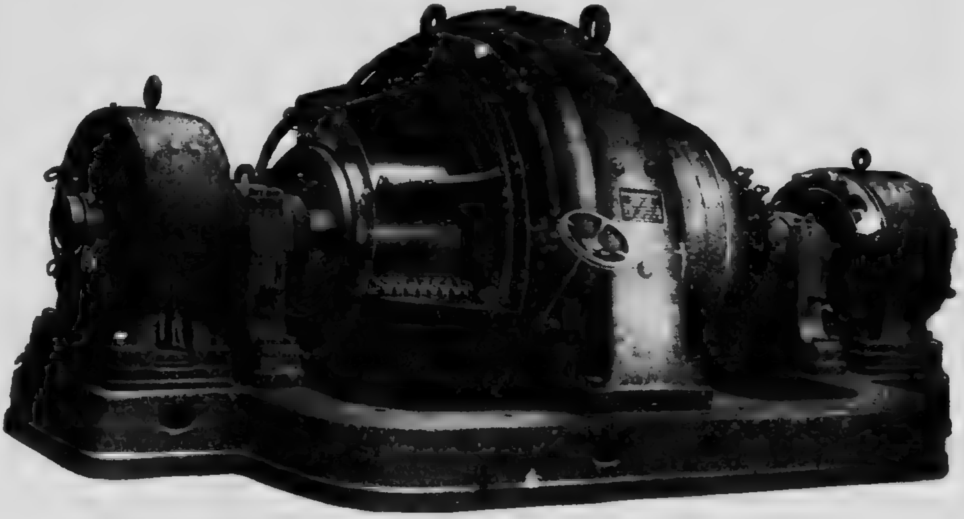


Fig. 1,029.—Westinghouse Rotary with Booster and Starting Motor, and with Separate Exciter for "Inverted Running."

to convert C.C. power into A.C. power. This method of using the machines is known as "inverted running."

Although the rotary converter is a reversible machine, the practical conditions of working, and therefore the methods of control, depend upon the kind of power supplied. If A.C. power be supplied the machine is an A.C. motor and a C.C. synchronous generator, with its speed fixed by the periodicity of the supply current; but if C.C. power be supplied, it is a C.C. motor and an A.C. generator, and the speed is not so controlled.

The result is that if from any cause the speed of the machine changes, the periodicity of the alternate currents generated will be changed, and with it the speed of any A.C. motors to which current is being supplied. Now an inductive load of A.C. motors or transformers will draw a lagging current from the generator, and such a current, as we have seen above, will tend to demagnetise the field magnets, and with the field so weakened the motor will speed up and the whole A.C. system may be thrown out of gear. The case indicated may arise quite suddenly by even a small induction motor with its heavy lagging starting currents being thrown straight on to the load.

This practical difficulty is met in two ways. The chief method is to use a direct-coupled *separate exciter* with a shunt-wound unsaturated field, so that if the rotary speeds up the voltage of the exciter, and its output of current to the fields of the big machine increases considerably, the tendency is for the speed to be checked, and the speed can only vary through narrow limit The other method is to add a *series winding* to the field of the rotary so that any increase in the continuous current caused by heavy lagging currents on the A.C. side strengthens the fields and automatically counteracts the tendency for the speed to increase. The separate exciter, however, remains the chief controlling influence.

A British Westinghouse rotary converter fitted with an exciter for inverted running is shown in Fig. 1,029. The exciter is fitted at the C.C. end of the shaft, the other end being fitted with an A.C. starting motor for the usual method of running. The machine is also provided with a booster, which for inverted running can be used to regulate the voltage supplied to the A.C. mains. If the A.C. load be non-inductive (*e.g.* glow lamps), or if the rotary be running in parallel with A.C. generators, the exciter may be dispensed with for reasons which will be apparent.

Turbo-rotary Working.—The difficulties of collecting heavy continuous current from high-speed turbo-dynamos have been referred to elsewhere (*see* pages 137 to 143 and 167 to 171). One method of dealing with the difficulty of using the high efficiency of the steam turbine as a prime mover consists in coupling the turbine to an alternator, and supplying the alternating currents generated to a multipole rotary. No static transformers need be interposed, as the alternator can be designed to give the required voltage to the rotary slip-rings. It is often better, however, to use transformers and generate at a fairly high voltage. In any case the rotary will run at a comparatively low speed, and the required heavy continuous currents can be easily collected from its large commutator.

VI.—MOTOR CONVERTERS

As explained fully elsewhere (*see* page 994), rotary converters, though efficient transformers of alternate current into continuous-current power, have the disadvantage that, within certain narrow limits, there is a fixed relation between the voltage on the slip rings and the voltage on the C.C. brushes. If, therefore, the alternate-current system of supply be, as it usually is, a high-voltage one, static transformers have to be interposed between the line and the slip rings, thus leading to increased capital expenditure and to complications in the switching and regulating. In fact, unless the A.C. voltage correspond to the desired C.C. voltage, an A.C. transformer must be interposed.

The motor converter, whilst being at a disadvantage in consisting of two machines, has the advantage that the stator can be directly switched on to the high-voltage supply mains, there being no conducting connection between the commutator of the continuous-current armature and the stator of the induction motor.

Diagram of Connections. The principle of the machine has already been explained in Vol. I., and an elementary diagram (Fig. 616) given of the connections. A more complete diagram of the connections of a modern Peebles motor converter is given in Fig. 1,030. For simplicity the machines shown diagrammatically are bipolar machines, though in actual practice considerations of frequency and speed necessitate the use of multipolar machines. The stator of the induction motor, which receives the high-voltage alternate current supplied, is represented by three star-connected windings, and the rotor by twelve coils, numbered 1 to 12, which in the bipolar rotating field set up by the stator will give a twelve-phase current to the rotor of the coupled continuous-current machine. The connections between the two rotors are, it will be remembered, made direct either along or through the shaft without the intervention of slip rings, thus differing from a "rotary" supplied from a static transformer,

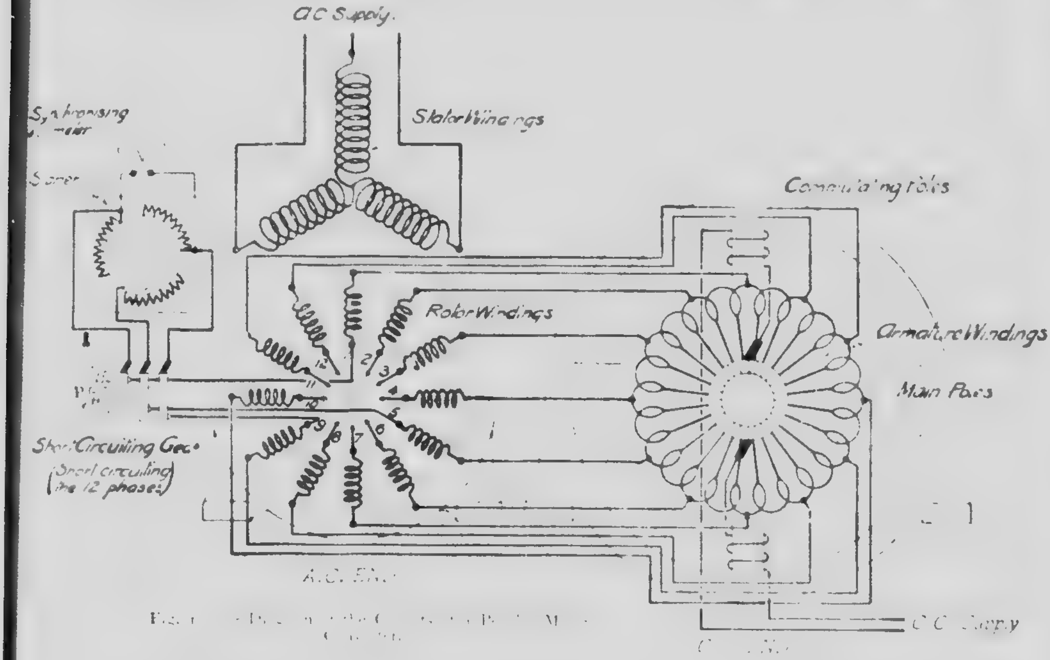


Fig. 1,030.—Diagram of the Connections of a Peebles Motor Converter.

with certain consequences to which allusion is made later. The carcass of the continuous-current machine is drawn quite diagrammatically in faint lines, and appears as having two main and two commutating salient poles projecting inwards from a common yoke ring. Only the windings on the commutating poles are indicated in the diagram, these windings being in series with the brushes and carrying the main current, which constitutes the continuous-current output. The main excitation would be by a shunt current drawn from the same brushes.

The diagram (Fig. 1,030) also shows the starting arrangements, which are of the usual type for an induction motor, a three-phase star-connected resistance being put in series with coils, 1, 5, and 9 on the rotor. When the proper speed and excitation have been attained as shown in a manner described later by the synchronising voltmeter, the resistance is cut out and the whole twelve coils are star-connected by the short-circuiting plug P.

As explained in Vol. I., if the two stators are wound for the same number of poles the proper synchronous speed is that fixed by half the frequency of the supply circuit. At this speed there is 50 per cent. slip in the induction motor, and half-frequency currents will be generated in its rotor; these currents will be of the right frequency to be picked up by the rotary converter action in the continuous-current armature, and will be rectified at its brushes, being superimposed on the other currents generated in the armature, which derive their energy from the mechanical power produced by the rotor of the induction motor and transmitted by the shaft to the continuous-current armature. Thus approximately half the power transmitted to the continuous-current load reaches the armature electrically, and half reaches it mechanically, due allowance being made for the usual unavoidable frictional, electrical, and magnetic losses.

The Actual Machines. The machines, which are built by Messrs. Bruce Peebles and Co., of Edinburgh, fall into two classes, namely: (i.) those in which the shaft is supported by two bearings only, these bearings being necessarily placed near the ends of the shaft; and (ii.) those in which a third bearing is introduced between the two rotors. It is obvious that the first method is by far the more convenient from many points of view, but cannot be applied to very large machines in which the weights of the rotating masses render an intermediate bearing necessary for mechanical reasons.

A two-bearing four-pole motor converter is shown in Fig. 1,031. It has an output of 150 kilowatts, and when supplied with main-line currents at 50 periods per second runs at a speed of 750 R.P.M. It is designed to convert three-phase alternate current power at 525 to 550 volts and 50 periods into continuous-current power at 220 to 240 volts. A rotary running at the same speed and supplied with 50-period currents would require eight poles and double the number of brush spindles which, with the same output and the same size of commutator, would, beside adding to the cost, increase the danger of flashing over if a short-circuit occurred. The chief advantages of being able to dispense with the intermediate bearing are that the electrical connections between the induction rotor and the C.C. armature can be carried along the outside of the shaft, and that the length of the whole machine, including the shaft and the bedplate, is shortened. These advantages have to be sacrificed on large machines for the reason given above.

A three-bearing machine having an output of 1,250 kilowatts is shown, as seen from the alternate-current end of the shaft, in Fig. 1,032. The number of poles and the speed of this machine illustrate in still another way the flexibility of the arrangements of a motor converter. With a 50-period supply the half synchronous speed would be 250 R.P.M. with 12-pole machines and 300 R.P.M. with 10-pole machines. An intermediate speed can be obtained by winding the rotor of the induction motor for 10 poles and making the dynamo a 12-pole machine. As the two rotors *must* run at the same speed, the result is that the rotor of the induction motor runs at a lower speed than 300 R.P.M., thus increasing the slip and the periodicity of the currents generated; whilst the armature of the dynamo, being supplied with these higher-period currents, runs at a correspondingly higher speed than 250 R.P.M. The actual speed of the shaft is nearly 273 R.P.M., at which the periodicity of the currents supplied to the armature of the dynamo is nearly 27·3 periods per second.

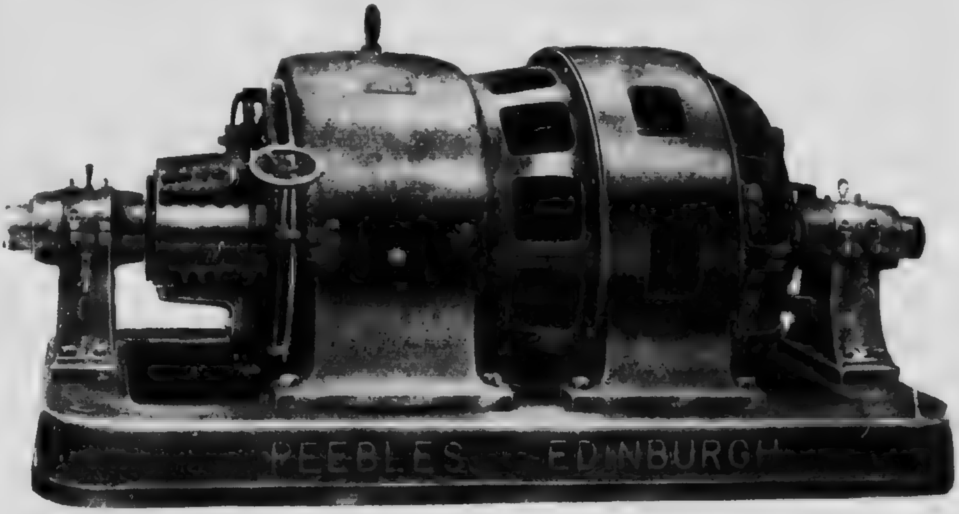


Fig. 1,031.—A Two-bearing 150-Kilowatt Peebles Motor Converter

The intermediate bearing requires that the shaft between the two rotors shall be hollow, so as to carry the twelve conductors from one to the other, the currents transferred by these conductors being distributed to the multipolar armature through the equalising rings. The six slip rings shown on the near end of the shaft are for starting purposes only, it having been found desirable on large machines to connect six of the twelve coils to the starting resistance instead of three as shown in Fig. 1,030. The hand wheel, the spindle of which passes through the bearing pedestal, is for the purpose of operating the short-circuiting gear (P, Fig. 1,030) when synchronism has been attained. The illustration (Fig. 1,032) also shows the barring gear between the two rotors which is necessary in the larger machines to enable the rotors to be revolved slowly for cleaning or other purposes when the machine is not running. This barring gear is not necessary for starting-up purposes. The device of the usual type for rocking the brushes which appears in Fig. 1,031 is only for use when the best position of the brushes for the conditions of service is being ascertained in the first instance. When this position has once been found there is no need for further change, as the machines will run sparklessly with fixed brushes at all loads. It is found more convenient to install the usual gear for this purpose than to make other arrangements for bringing the brushes to the best position as shown by actual experiment.

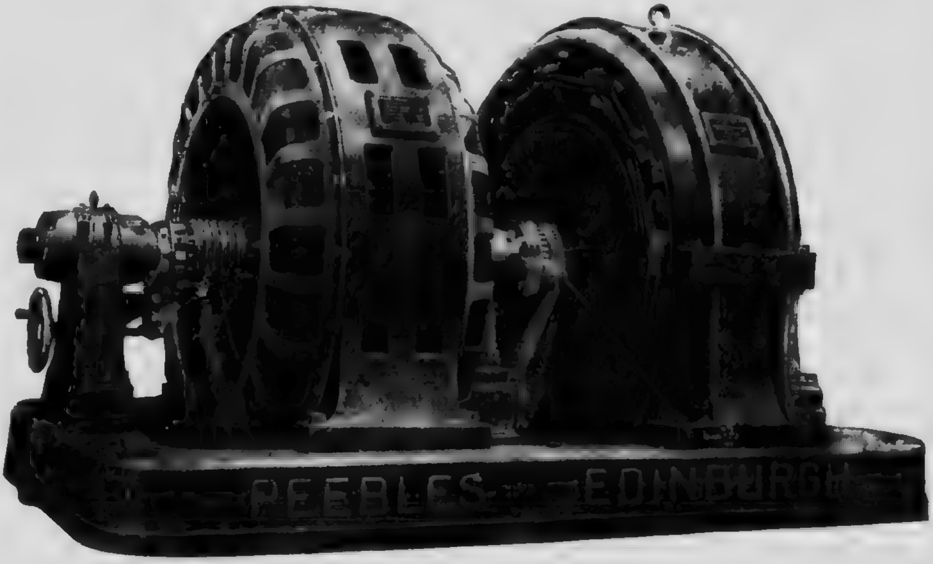


Fig. 1,032.—A Three-bearing 1,250-Kilowatt Peebles Motor Converter.

Starting.—A motor converter can be started up from the continuous-current side with an ordinary continuous-current starter of proper design for its size, and on coming up to speed can be synchronised and thrown on to the alternate-current leads in exactly the same way as an alternator.

One of its chief advantages, however, as compared with a rotary is the simplicity of the method by which it can be started up from the alternate-current side. The connections being as shown in Fig. 1,030, with no load and the field circuit open at the continuous-current end, the main switch on the supply mains is closed and the full voltage thrown on to the stator windings. The rotor starting resistance is, of course, all in, joining three (or six) of the twelve rotor windings through resistances to a star or neutral point. It must not be overlooked that the rotor windings are also connected through the "mesh" circuits of the continuous-current armature. If the machine does not start at once, the starting resistances are gradually cut out until it does start, when it is allowed to run up to about 10 per cent. above normal speed. The regulating resistance in the field circuit on the continuous-current side must be adjusted so that the machine commences to excite when this speed is reached. The reading on the synchronising voltmeter V (Fig. 1,030) decreases as the machine runs up to speed, but, as soon as the continuous-current fields excite, the speed commences to fall and the voltage rises. As the synchronous speed is approached the voltmeter pointer commences to oscillate, and the oscillations become slower as the synchronous speed is being reached. When the oscillations are quite slow and the pointer of the voltmeter is momentarily at zero, the starting resistances are cut out and the induction rotor windings "short-circuited" by the special device. The machine is then in perfect synchronism and is ready to take its load.

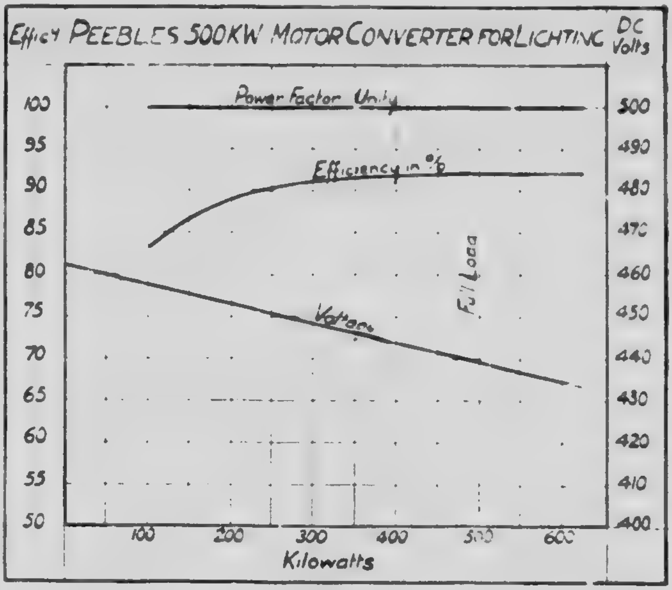


Fig. 1,03[illegible].—Per[illegible] Curves [illegible] K[illegible] M[illegible]

With large machines only one fixed non-adjustable t[illegible] are [illegible]sed. Such adjustment as is necessary for synchronising is made in the field regulator at the continuous-current end, the starting resistance [illegible] short-circuited at the moment when synchronism, as shown by the volt meter, is attained. No complicated synchroniser of any of the types described in Chapter III. is required.

The current taken at starting under the above conditions varies from one-fourth to one-third of the normal full-load current. It depends upon the magnetising current required by the induction motor.

Performance Curves. The performance curves of two 500-kilowatt motor converters are given in Figs. 1,033 and 1,034. In Fig. 1,033 the machine is shunt wound for its main excitation, and is arranged to have a 5 per cent. drop from no load to full load. Such a drop, or even greater drop, is desirable in certain sub-station working, for instance if there [illegible] a battery "floating" (*see* page 538) on the busbars. A larger drop can be arranged, if required, by negative compounding. The curves are plotted to a load base, and show (i.) the voltage drop (462 to 440 volts), (ii.) the efficiency, and (iii.) the power factor. The over-all efficiency rises to [illegible] per cent. at half load, and to 92 per cent. at full load and at 20 per cent. overload. The remarkable point about the diagram is that for all loa[illegible] power factor is unity.

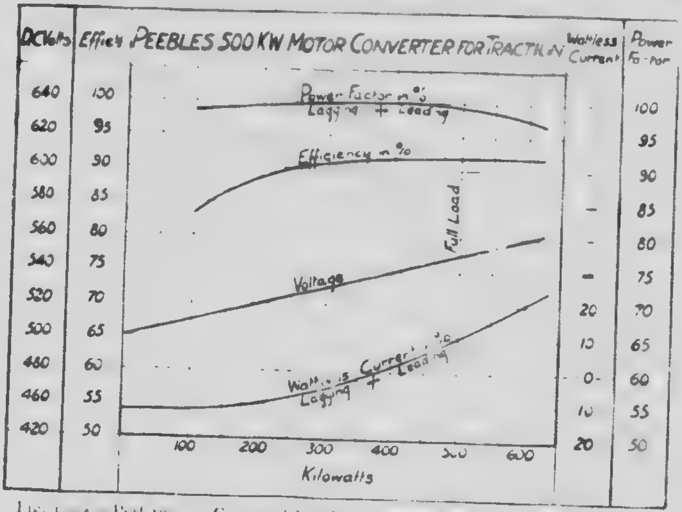


Fig. 1,034.—Performance Curves of Peebles Compound-wound 500 Kilowatt Motor Converter.

The curves in Fig. 1,034 are for a machine compound wound for traction work. In this work a 10 per cent. rise in the voltage from no load to full load is often required, and is shown on the diagram in which the voltage rises from 500 volts at no load to 550 at full load and 560 at twenty per cent. overload. The efficiency from half load onwards is nearly, but not quite, as good as in Fig. 1,033. The power factor, which is unity at

375 kilowatts, is slightly lagging. [illegible] lower loads [illegible] down to [illegible] k[illegible] but at higher loads up to 625 kilowatts (25 per cent. overload) [illegible] power factor. The corresponding watt[illegible] lower part of the diagram. The leadin[illegible] lagging wattless currents in other parts of the [illegible] and [illegible] this current the set, as explained elsewhere, acts [illegible]

Theory.—There are one or two outstanding [illegible] which are not touched upon in other parts of this section [illegible] section on rotary converters.

Voltage regulation is much simpler in a motor converter than in a rotary and a wide range is ordinarily obtained by varying the resistance in the shunt excitation circuit of the continuous-current end. This is rendered possible by the high reactance at the alternating-current end. For instance, with a certain plant the continuous-current voltage was capable of variation from 400 volts for lighting supply to 600 volts [illegible] work, the *power factor* remaining near unity throughout.

On starting the continuous-current voltage always comes up with the right polarity. This is due to several interacting causes, among which may be mentioned the residual magnetism in the field which, as in a C.C. dynamo, determines the polarity set up by self-excitation, and the drawing off of excessive currents [illegible] through the starting resistance; the fact that the starting currents are leading currents, the A.C. rotor being the rotor of an [illegible] motor [illegible] to be k[illegible] d. The action is also assisted by the fixed mechanical connection between the coils on the two rotors.

The poles of the generator are provided with damping coils in the shape of rods which increase the strong synchronising forces tendency to keep the machine in step. The existence of these forces makes it easy to obtain smooth, parallel running with other machines, "hunting" troubles being said to be unknown. In fact the motor converter will keep in step under very severe conditions [illegible] circuit. It also quite easily follows any periodicity variations in the alternate-current supply circuits.

Commutation [illegible] motor converter is practically perfect under all conditions [illegible] due, as in the rotary, to the effect of the combined action [illegible] r and the generator currents. The 12-phase current [illegible] explained [illegible] (*see* pages 977 and 990), helps and tends to re[illegible] a matter [illegible] on. But the outstanding difference is that, as compared with a rotary, the armature is called upon to act more completely as [illegible] rator armature and to convert a large amount of mechanical power [illegible] d by the shaft into electrical power. Commutating poles [illegible] re effectively employed as in a dynamo to counteract [illegible] -action, which is greater than in a rotary.

[illegible] noted elsewhere (*see* page 1011) that the *speed* of the machine may be varied by making the number of poles at the two ends different. It can easily be shown that the synchronous speed is given by the equation:—

$$\text{Speed (R.P.M.)} = \frac{120 \times \text{periodicity of supply}}{\text{Sum of the poles in the two machines}}$$

In practice, however, the two machines usually have the same number of poles, and the difference is never greater than two. One incidental advantage of reducing the number of poles in the induction motor is that a smaller machine will suffice as a smaller proportion of the received energy is converted into mechanical power. This advantage cannot, however, be pushed far in practice, because of difficulties arising in other directions.

It should be pointed out that the full-load efficiency of a rotary set (including the transformers) is about 1 per cent. higher than that of a motor converter, although at the lower loads this difference is not so marked. It is claimed also for the rotary that as there are no voltages in the machine higher than the continuous-current voltage the risk of a breakdown of insulation is reduced. The risk is, in fact, transferred to the transformers, the coils of which are more easily repaired than the coils of the stator of an induction motor.

In conclusion, for the same reasons which apply in six-phase rotaries, the short-circuited ends of the windings of the induction motor are all at a constant potential, which is halfway between that of the + and — brushes on the commutator. This point may therefore be connected to the neutral wire of a three-wire c.c. distributing system, the brushes being on the outers. The motor converter, as explained elsewhere (*see* page 1307), will then act as a "balancer" tending to keep constant the potential of the neutral wire of the distributing system, and will act efficiently even when the out-of-balance current is very heavy. Both rotary and motor converters can also be used as **"phase advancers"** (*see* pages 1002, 1006 and 1312).

CHAPTER IX

SECONDARY CELLS OR ACCUMULATORS

CHEMICAL TRANSFORMERS

In the previous editions of this book it was only possible, owing to exigencies of space, to treat the important subject of secondary cells from the historical and general standpoint, and the projected section on technical developments and details has been crowded out by the rapid and important technical developments in other departments of electrical science. In the present edition the increase of size makes it possible to find some, though not very adequate, space for references to the technology of the subject.

The principles upon which the action and construction of a secondary cell are based have been fully explained in Vol. I., and the early forms, and some of their immediate successors, have been described. The present chapter chiefly deals with modern cells now in common use, and the technical points which arise in their adaptation to the service of man.

The period which has intervened since such matters were previously dealt with here has been, in the case of *Lead secondary cells*, a period in which defects, which have appeared in practice, have been carefully studied, and many patient attempts made to remedy them. It remains as true to-day as it was thirty years ago, that the manufacture of secondary cells depends for its success on unremitting attention to minute details, and that no point, however small, in which improvement appears possible should be neglected. During the greater part of the period named the only secondary cell which had any commercial value was the lead cell, first made a practical success by the genius of Planté and Faure. During the last decade, however, the *Nickel-Iron-Potash secondary cell* has, with phenomenal patience, and after almost infinite experiment, been developed by Edison to the point of practical success, and since 1911 such cells have been placed on the market in large numbers, and have taken a recognised position in the resources of the electrical engineer. The two types of cell, though based ultimately on the same scientific principles, have so little in common from the technical standpoint that at the present stage it will be convenient to deal with them separately, though comparisons must necessarily be made. We take the older type first.

I.—THE MODERN LEAD SECONDARY CELL

The inherent defects, as well as the possibilities, from an engineering standpoint of the lead secondary cell were recognised quite rapidly and widely within a few years of the epoch-making invention of the Faure cell, and numerous inventors devoted their abilities to overcoming these defects and developing the possibilities. The points to which attention has been chiefly directed may be briefly summarised as follows:

- (i.) The diminution of the great weight of the early cells as compared with their capacity for storing energy.
- (ii.) The ensuring that the active material (peroxide of lead on the +ve plates, spongy lead on the −ve) shall adhere firmly to the conducting backing to which it is attached, and not, by dropping off, shorten the working life of the plate.
- (iii.) The increase of the *rates* of discharge and charge without injury to the plates.
- (iv.) The reduction of the ohmic resistance, not only of the cell itself, but also of all external lugs and connectors, and incidentally the distribution of the current evenly over the plates, which means not only a diminution of resistance, but also has other advantages
- (v.) The prevention of the formation of the higher sulphates of lead, otherwise known as sulphating.
- (vi.) The prevention of internal short circuiting by buckling, treeing, and otherwise; and
- (vii.) The development of an effective automatic control which shall, without the continual intervention of an attendant, regulate the charging and discharging of batteries and fit them to perform, under widely different conditions, all the functions of which they are theoretically capable in generation, transmission, and utilisation systems.

II.—THE DESIGN AND FORMATION OF THE PLATES

Keeping these points in view, modern methods of manufacturing the plates of a secondary cell may next be referred to. In the early years of the commercial development of the secondary cell which followed Camille Faure's invention in 1881, inventors and manufacturers were divided as to the relative merits of the two methods for forming the plates, each of which, by that time, was up to a certain point a practical success. These methods are to-day known as the "pasted" method, based upon Faure's inventions, and the "Planté" method, based upon Planté's still earlier experiments. The net result of all the work which has been done is that the Planté method, suitably modified and developed, is almost universally made use of for the manufacture of the +ve plates, and the pasted method is quite as generally utilised for the manufacture of the –ve. It will therefore be convenient to deal with these two classes of plates separately.

The Formation of Positive Plates.—For general power purposes the positive plates in the most widely used cells are now almost invariably of the Planté type, in the original formation of which Planté (*see* page 204, Vol. I.) started with plates of metallic lead. The commercially fatal defect, as already explained (*loc. cit.*), of this method is the length of time (months) necessary to produce a plate of reasonable capacity, and the ingenuity of inventors has been successfully applied in elaborating more than one method by which this defect is minimised, whilst ensuring that the outstanding advantage of the Planté method—namely, the more stable and intimate contact between the active material and the plate backing—is not sacrificed.

For convenience it will be well first to describe the various designs of the lead backing or frame on which the active material is to be formed, and then to refer to some of the principal methods adopted for shortening the period of formation.

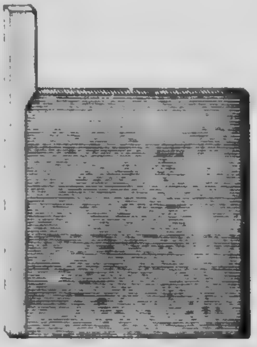


Fig. 1,035.—Early Dujardin Planté Unformed Plate

The Lead Backing or Frame.—The particular shapes adopted are designed generally (i.) to increase the surface of metallic lead exposed to electrolytic or chemical action in a plate of given length and breadth, (ii.) to supply sufficient and properly distributed metallic conducting material for the current, and (iii.) to combine with [illegible] objects sufficient mechanical stiffness, a property in which lead as a material is somewhat deficient.

Planté's plates were originally of rolled or cast lead. To increase the area of surfaces exposed, these surfaces have been roughened by scoring or otherwise. An early Dujardin-Planté method is shown in an unformed plate in Fig. 1,035. This plate was built up of thin strips of sheet lead laid loosely on top of one another, and with their ends burnt into stout vertical supports of lead.

The lineal descendants of these plates are manufactured by the D.-P. Battery Company, Limited, of Bakewell, Derbyshire, who have carried on and developed the Dujardin-Planté methods in this country for many years. A modern D.-P. +ve plate, is shown in Fig. 1,036, in which a portion of a plate is depicted lying flat. When in the battery the laminations run vertically instead of horizontally, as in the original pattern seen in Fig. 1,035. There is a very slight rib, not shown in the figure, running down the middle of each strip; but, what is more important, the strips

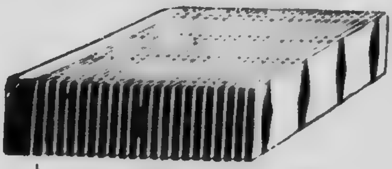


Fig. 1,036.—Section of "D. P." Positive.

are bound together at intervals of about 1 cm. by stout horizontal bands, the lozenge-shaped sections of which are visible on the right-hand side of the figure.

This pattern of plate is now widely used for the $+^{es}$ of modern secondary batteries, as can be seen in Fig. 1,037, which shows part of an unformed + used by Messrs. Pritchett and Gold and Electrical Power Storage Company, Limited, the plate being cut along A B to show the cross-section. The vertical strips running from C to D are thickest in the middle of the plate, and taper off towards the open clearance in the cell. In this way the penetration of the electrolyte is facilitated. The plate is stiffened by binding strips of lead as shown at *a b*. A complete plate is shown on Fig. 1,038, from which it will be seen that vertical strengthening strips are also provided, especially at the two upper corners. The peculiar shape of the lugs is referred to later (see page 1033).

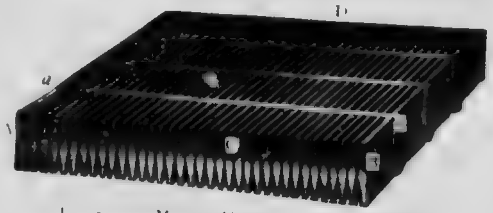


Fig. 1,037.—[illegible] Plate Positive.

Another example is given in Fig. 1,039, which depicts the pattern of Planté $+^{es}$ made by the Hart Accumulator Company, Limited; this should be compared carefully with the preceding examples. As previously pointed out, these modern plates are stiffened at intervals with heavy horizontal ribs, which are continuous from side to side of the plate; Figs. 1,036 and 1,039 show parts of the heavy lead frame and the stouter cross ribs which give the necessary mechanical support and stiffness to

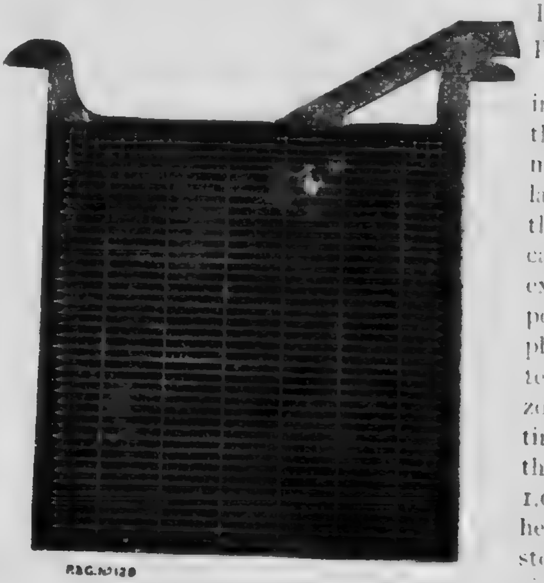


Fig. 1,038.—Complete P. & G. and E. P. S. Planté Positive Plate.

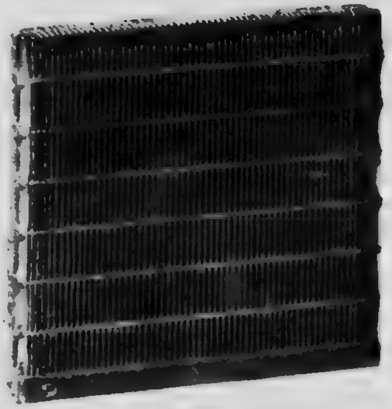


Fig. 1,039.—H[illegible] Planté Positive.

these thin laminations. The standard thickness of the completed plate from front to back is from 0·9 to 1·0 cm., and the stiffening ribs are also about 1 cm. apart. These plates weigh between 14 and 15 lb. per square foot of plate.

A completed plate with the lugs at *a* and *a*, for supporting it from the sides of the cell, and the extended lug 1 for connecting it to other plates and cells is shown in Fig. 1,040, which depicts a +ve plate of the "Plantide Accumulator" manufactured by the Chloride Electrical Storage Company, Limited. The standard size of plate varies from 4 inches square up to 27 by 15 inches.

Positive plates of this type are designed, as already mentioned, to provide for a free circulation of the electrolyte so as to bring it into contact with all the exposed surfaces of the plate, which obviously have a total area many times that of the vertical area of the face of the plate as a whole.

The method of construction also enables the manufacturer to obtain large storage capacity per square foot of the plate face with such a thin skin of peroxide as will not weaken the metallic support by eating it away. This peroxide, formed electrolytically as in the original Planté cell (*see* Vol. I., pages 205 and 206) consists of a hard, thin adherent skin of a durable nature, which withstands heavy rates of charge and discharge. Further, the ample quantity of metallic lead in the frame and ribs provides good conducting paths for the current, and tends to distribute it uniformly over the plate, besides keeping the internal resistance low.

The "Chloride" +ve.—The "Chloride" secondary cell manufactured by the Chloride Electrical Storage Company, Limited, dates back to 1888, and has

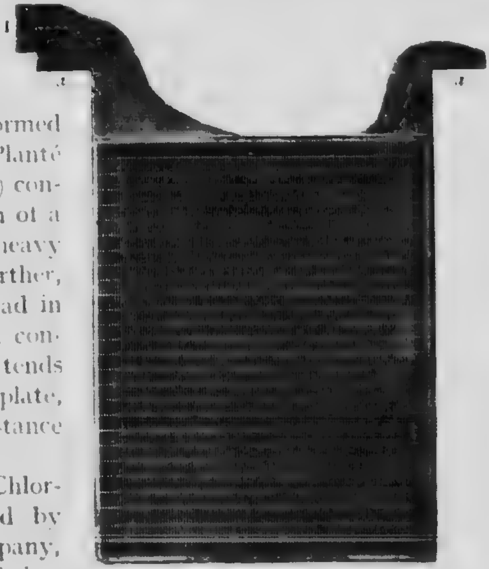


Fig. 1,040.—The "Plantide" +ve Plate

always had Planté positives. The modern "Chloride" positive plate is shown in Fig. 1,041 and has many of the distinguishing features of the early patterns, though improvements have doubtless been introduced from time to time. The grid, or backing, is made of a lead-antimony alloy, containing from 2 to 4 per cent. of antimony, which has been found very suitable for accumulator grids, as it has great mechanical strength and is not affected chemically by the acid and other materials with which it comes into contact in a lead secondary cell.

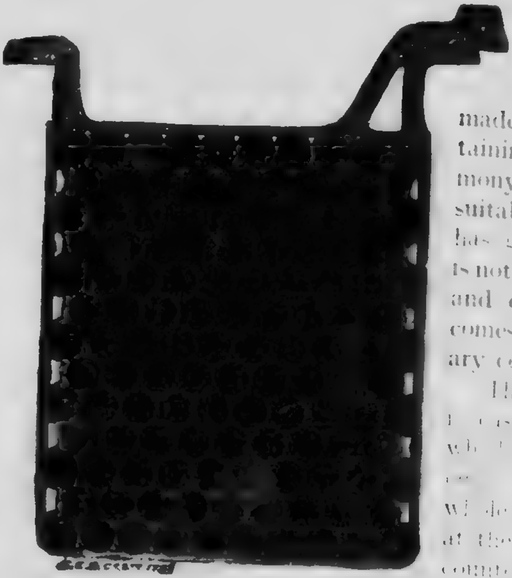


Fig. 1,041.—+ Plate of the Chloride Co.

The alloy as shown in Fig. 1,041 is cast into a geometrical pattern, which [illegible] of a number of circular cells arranged diagonally, the whole plate having substantial lugs at the upper corners. The holes are countersunk on both sides, as shown on a larger scale in Fig. 1,042. The active material is formed from pure lead tape, which is pressed cold in a press working at a pressure of 4,000 lb. per square inch, two tapes being produced simultaneously and wound on to reels, each of which carries 2 cwt. of tape. This tape is next fed into a "rosette" machine, which crimps the edges, cuts off the requisite length, and winds it into a rosette, the capacity of the machine being 2,000 rosettes per hour. The rosettes are next placed in a filling template of the size of the plate which is being manufactured, and this, being placed over the cast grid, the whole of the rosettes are driven home each into its respective cell by one squeeze of a hydraulic press. The squeeze expands the rosettes into the countersunk holes, where they are securely retained.

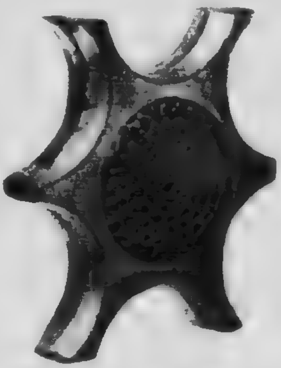


Fig. 1,042.—Single Rosette of Chloride Plate.

The lead tape is then converted largely into active peroxide of lead by placing the unformed grids containing the rosettes between dummy negatives in an electrolyte of dilute sulphuric acid containing a forming reagent which curtails the time of formation probably by biting into and thus roughening the surface of the lead by ordinary chemical action. A tough skin of lead peroxide is thus produced without weakening the metallic lead base

The "Hart" Demi-Planté +ve.—These positives, manufactured by the Hart Accumulator Company, are, as their name implies, only partially Planté positives. The lead grid or backing is to some extent a reversion to an old E. P. S. pattern of pasted positive, the modification being that the ribs are more numerous, there being from nine to twelve to the inch, and that they are thicker throughout and are supported by vertical binding strips at distances of 1½ inch apart, as is shown in Fig. 1,043. It will be noticed that a substantial quantity of lead is used, and this is an essential part of the design. The ledges formed by the ribs are filled with special peroxide paste, very porous and permitting of fairly free circulation of the electrolyte in the pores. The plate with the paste in place is shown in Fig. 1,044.

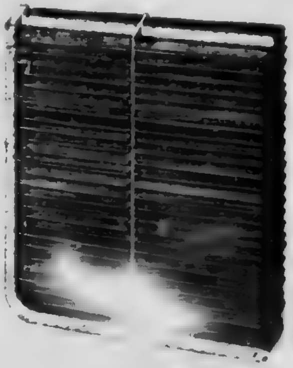


Fig. [illegible] Hart [illegible]

In the early period of its use this plate behaves as a pasted plate; but as it is charged and discharged a skin of peroxide is gradually formed all over the surface of the lead of the grid. Under the circumstances it is formed quite slowly, and it is claimed that it is tougher and more homogeneous than oxide formed *in situ* by electro-chemical action. The result is that after several years of working, although the pasted material which was initially filled into the plate may have disintegrated, its place is taken by the electrolytically formed oxide. Frequently it happens that the capacity of such plates is higher after several years' work than it was at first. The central diaphragm is sufficiently thick to prevent buckling under heavy discharges up to the maximum rates specified by the manufacturers.

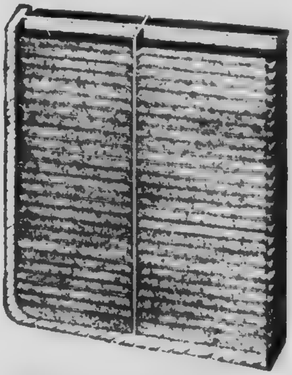


Fig. 1,044. Hart Demi-Planté Positive Plate

The Ironclad Exide +ve Plate.—This plate, specially designed for use on electric vehicles, and manufactured by the Chloride Electrical Storage Company, Limited, is radically different in mechanical design from the positives which have been described above. Following a practice which has been used by more than one inventor, the active material is arranged

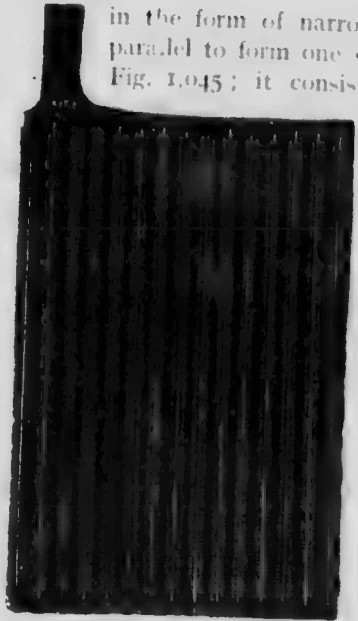


Fig. 1,045.—The Ironclad Exide + Plate.

in the form of narrow pencils, a number of which are placed in parallel to form one + plate. A completed plate is shown in Fig. 1,045; it consists of a number of vertical pencils, each about $\frac{3}{8}$ inch in external diameter, joined top and bottom to horizontal bars. A vertical section of a pencil on an enlarged scale in given in Fig. 1,046. It contains a central conducting lead core c, placed inside a concentric ebonite or hard rubber tube T T, which has a large number of horizontal slits cut in it. The active material, peroxide of lead, is packed in the space between the core and the tube. A horizontal section of a few neighbouring tubes, assembled in their relative positions, is given in Fig. 1,047. It is found in practice that the slits allow the acid free access to the active material, whilst they are sufficiently fine to prevent it being washed out. Each ebonite tube has two vertical ribs projecting on opposite sides at right angles to the face of the plate. These not only stiffen the somewhat thin ebonite, but they also act as spacing strips, taking the place of the ribs on the wooden diaphragms used in "exide" plates (*see* Fig. 1,050), and allow the use of plane wood diaphragms, one on either side of each row of tubes, as seen in section in Fig. 1,047. In the same figure the adjacent negative plates are indicated diagrammatically by section lines. From the same figure it will be noticed that the working portion of the electrolyte is carried in the interstices between the cylinders, and is therefore within the confines of the plate itself. The standard size of positive plate contains fifteen of the tubes (*see* Fig. 1,045), and its over-all dimensions are $5\frac{3}{4}$ inches by 8 inches by $\frac{7}{16}$ inch. Its rated output is 32 ampere-hours in five hours, which gives a current density reckoned on the vertical area of 10 amperes per square foot. The negative plate is of the firm's standard type (Fig. 1,050), but of somewhat greater thickness.

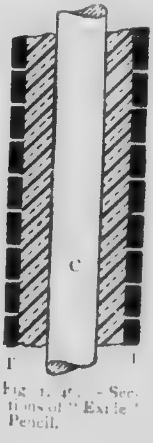


Fig. 1,046.—Sections of "Exide" Pencil.

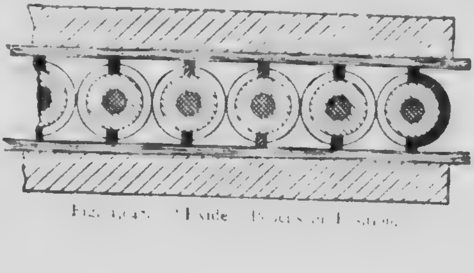


Fig. 1,047. "Exide" [illegible]

Methods of Accelerating Formation.—The modern practice is to form the positives quite separately from the negatives, and when electrolysis is employed dummy negatives are used. In the original Planté process the formation, as already mentioned, is wholly electrolytic, and the "ampere-hour efficiency" of the process is very low. In other words, the ampere hours supplied during formation are many times the rated output of the finished positives. Notwithstanding the heavy capital expenditure for plant and the necessary space accommodation, and the cost of the necessary current energy, the process is still used commercially, and in one instance the manufacturers, by taking full advantage of the knowledge obtained by years of experience and research, are said to have reduced the period of formation to six weeks of continuous day and night working. This is probably the shortest time in which good positives have been made by the original Planté process, namely, with dilute sulphuric acid only for the electrolyte.

In a large number of methods the time of formation by electrolysis is considerably shortened by the addition of oxidizing agents to the electrolyte; in other words, by using a special "forming solution." These solutions are obtained by adding a salt of some other acid, such as nitric acid or acetic acid, to the dilute sulphuric acid. Nitrate or nitrite of soda is one of the salts largely so used, but a great number of salts have been tried more or less successfully. The forming solution is only used for the preliminary period of this formation, which is concluded at a definite stage, when the partly formed plates must be thoroughly washed to remove all traces of the forming solution before the formation is completed electrolytically in pure dilute sulphuric acid.

The action in any of these forming solutions is very complex, and great care and skill are required to obtain a uniformly satisfactory result, but it has been found possible by their use to increase the "ampere-hour efficiency" of formation to 25 per cent. Many complex ionic combinations are formed and give rise to complicated reactions, but in the main the operation consists of two actions proceeding continuously, almost simultaneously, one being only a little in advance of the other. The first action consists in the oxidation of the lead, either chemically or electrolytically, and the second in the peroxidation of the resulting compound.

In quite another series of methods, of which the Epstein process is a notable example, the first of these actions is carried through separately by a purely chemical reaction. In the Epstein process of formation the plates are first oxidised by being boiled in very dilute nitric acid, and then dried in air. The formation is then completed electrolytically in dilute sulphuric acid. Other methods of obtaining the preliminary oxidation have been described in previous editions of this book.

The Formation of Negative Plates.—Although the Planté method of forming —ves is not entirely discarded, the —ve plates of modern secondary batteries are almost invariably of the type referred to more than once above as "pasted" plates. This means that they are plates made according to Faure's general method from a diluted sulphuric acid paste of suitable lead oxides applied to a suitably shaped lead grid and then "formed" electrolytically. As explained elsewhere, the —ve active material should, on a fully charged cell, consist of spongy lead. Experience has shown that there is less difficulty in keeping such material in conducting contact with the lead frame or backing of the —ve plate than there is in retaining the lead peroxide on the +ve plate when formed similarly from lower "pasted" oxides. For —ve plates, therefore, the necessary adhesion being secured, full advantage can be taken of Faure's method of shortening the period of formation. The ingenuity of inventors has been chiefly directed to the design of the grid or backing so as to secure the maximum power of retention of the active material in intimate contact with the grid.

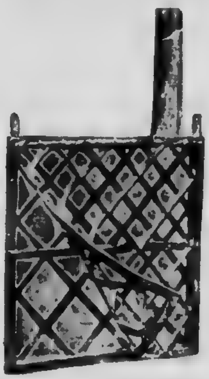


Fig. 1,048.—Lattice Frame for Small Negatives.

A simple method of satisfying the conditions, which, however, has only been applied to quite small cells, is used by Messrs. Peto and Radford. It consists in the employment of a hollow frame formed by two relatively wide lead lattices burnt on to a substantial rectangular supporting frame of lead provided with a substantial lead lug for an electrode. The lattices are staggered on the two sides, as shown in Fig. 1,048, in which one of them has been turned back to exhibit the method of construction. A complete plate is shown in Fig. 1,049.

For larger plates much ingenuity has been exercised in devising supports for the active material which, whilst fulfilling the mechanical and electrical conditions, can be manufactured easily and cheaply. The methods of overcoming the various difficulties inherent in the problem will best be realised by the description of a few successful solutions of the problems involved.

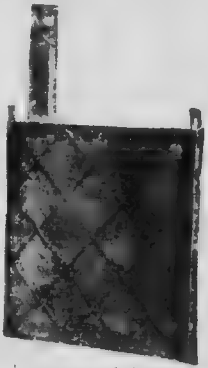
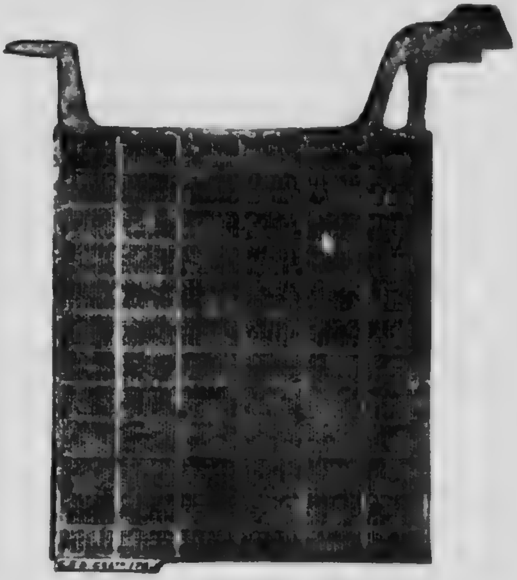


Fig. 1,049.—A Lattice Negative.

Box Type —ves.—A general type of negative plate which is used by more than one firm of manufacturers is the "box" type, in which the active material is contained in a kind of lead box with perforated sides. The details of construction, which are, of course, important, differ more or less widely with different manufacturers, as will be realised from the following examples.

In this form of plate the active material used expands slightly during the working processes, the expansion being sufficient to ensure good mechanical contact without forcing the paste through the holes of the lead screen, which would detach it altogether from the plate. The electrolyte passes freely through the perforations of the screen.

"*Chloride" Accumulator* [redacted].—The lead framework of the "box" negative of the Chloride Electrical Storage Company is shown in Fig. 1,050. It consists of two frames of a lattice pattern of 1½ inch squares closed on one side with thin sheet-lead perforated with about two hundred holes per square inch. Two plates, with the perforated sheets on the outside are riveted together after the introduction of the paste of litharge from which the active material is to be formed by electrolytic reduction. This formation can be carried out, if desired, after the cells are assembled at the installation. It will be noticed that the result is a series of small boxes or cages into which the oxides can be packed; the material is retained in these boxes primarily by the finely perforated sheet of lead, to which the grids on both sides add the necessary mechanical stiffness. It is claimed for this method of construction that the electrolyte has free access to the interior of the plate, and that the capacity of the plate can be maintained practically constant over a long period of years.



[illegible] [redacted] Pla[illegible] "C[illegible]

"*D. P." [redacted]*.—The negatives of the D. P. Battery Company are very similar to the above, and the process of manufacture follows the same lines, as will be seen from inspection of the completely formed [redacted] shown in Fig. 1,051, in which the rivets which hold the lead lattice frames together can be observed. These rivets are at the junctions of every third vertical, [illegible] every second horizontal rib, and on every horizontal rib at the vertical boundaries. They assist in holding on the finely perforated lead sheet with which both sides of the plate are covered.

Pritchett and Gold [redacted].—The box type of [redacted] is also used by Messrs. Pritchett and Gold, and the Electrical Power Storage Company, as is shown in Fig. 1,052, which depicts a sectional view of a portion of a plate very similar to those above described, and which needs no further explanation, though attention may be called to the special strengthening of the lattice at alternate corners and to the fairly massive bars and distance pieces which form a supporting framework. A complete plate is shown in Fig. 1,053, in which it will be seen that the lattice is still further strengthened at the upper corners. The curiously shaped lugs are referred to later (see page 1033).

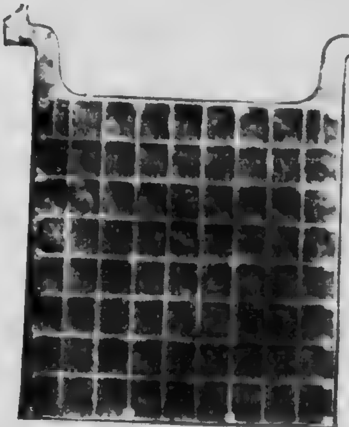


Fig. 1,053.—A D.-P. "Box" Negative.

Grid Type [illegible].—In this type of negative, which in one form or another has been very extensively used in the past, a supporting grid with numerous interstices is made in one piece, usually by casting. It may be said generally that the conditions for effectively retaining the paste in the interior of the grid are antagonistic to the conditions for making a successful casting and the ingenuity of inventors has been directed to the design of patterns which reconcile these conflicting conditions. In previous editions examples have been given of grids in successful use in the past, and the following is an example of grids now made.

"Hart" Accumulator [illegible].—The [illegible] grid made by the Hart Accumulator Company is somewhat complicated, as is shown in Fig. 1,054. The material used is the antimonial lead referred to elsewhere as being useful in secondary batteries, and the grid is cast in a chilled metal mould consisting of two halves, which are brought together after the molten metal has been poured into one of them. The complicated casting which would at first sight appear impossible to produce is thus successfully accomplished. It should be noticed that the vertical ribs with their little holding-in rectangles alternate on the opposite sides of the plate. The paste is pressed into the hollows provided, and after preliminary drying the formation of the plate is completed electrolytically. During this process the pasted material, as has been already mentioned, expands somewhat, and is thus securely held in the interstices.

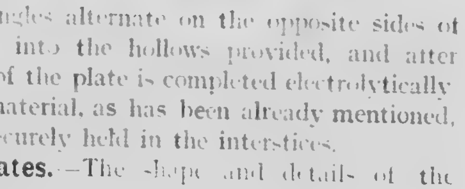


Fig. 1,054.—Sectional View of [illegible]

Manufacture of Pasted Plates.—The shape and details of the id or container having been settled, the next step is the introduction of the lead oxide, which will eventually be reduced or peroxidised as the case may be, by electrolysis.

As explained in the historical notes, Faure used *red lead* Pb_3O_4, otherwise known as *minium*, as his starting point. This material is manufactured in large quantities as a regular article of commerce for other purposes. It appears to be a mixture of the monoxide, litharge, PbO, and the peroxide PbO_2, but the actual commercial article may vary in composition as to the quantities of the two oxides present and may not therefore be always correctly represented by the formula Pb_3O_4. Minium is used as the starting point for such pasted **+** as are still manufactured, but for **−** the lower oxide, litharge, PbO, is more generally employed, since the amount of oxygen to be removed is less. The theoretical quantity of electricity required to reduce or to peroxidise one pound of litharge is 109 ampere-hours, whilst to reduce one pound of red lead requires 147 ampere-hours, and to peroxidise it requires 71 ampere-hours.

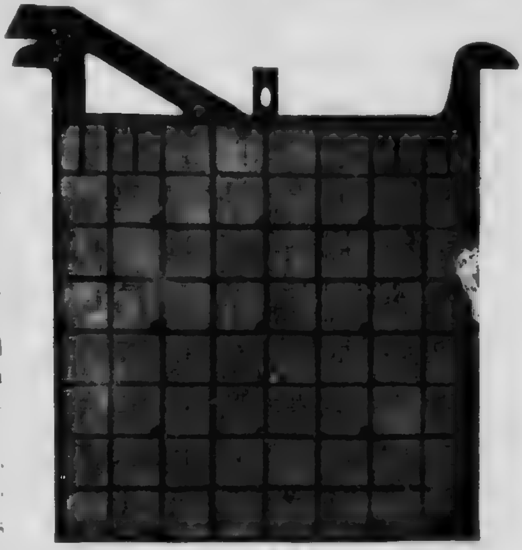


Fig. [illegible] — [illegible] Negative Plate.

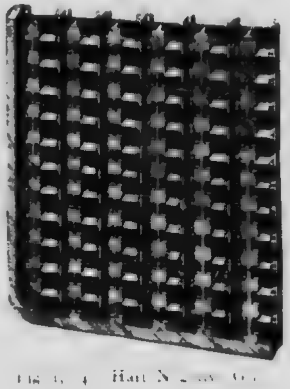


Fig. [illegible] — Hart Negative Grid.

The first step is to make the lead oxide used into a "paste" by mixing with dilute sulphuric acid of a specific gravity between 1·100 and 1·200 at 60° F. The liquid is added in small quantities to the powdered oxide and thoroughly mixed in until the result is a kind of stiff mortar, somewhat greasy. Great experience is needed to produce a good result, for if too much liquid be added a rather than paste is produced, which does not give satisfactory results. Many slight modifications of the method have been used from time to time, with more or less success, to improve on the process, and machines have been invented for the purpose, but have not had a very conspicuous success.

After mixing, the paste is applied to the support and sometimes forced into contact with it by pressure. According to the form of the support, special devices are employed to ensure good and lasting contact. The paste is then allowed to harden, or "season," as it is called, by exposure to the atmosphere, though the process may be hastened by the use of a moderately heated drying chamber. If the ordinary atmosphere be used, this part of the process may take days or even weeks. The hardening is due to slow chemical action which may be of the nature of hydration.

When "seasoning" is completed the plates are transferred to the forming tanks, in which the electrolyte is dilute H_2SO_4 of specific gravity 1·100 to 1·200, dummy + being used for the formation of −, and dummy − for the formation of +. The current employed depends upon the particular type of plate under treatment, and may vary from one ampere to four amperes per pound of oxide. The time of formation will obviously depend upon circumstances, but the necessary ampere-hours need not be much in excess of the theoretical quantity. Thus, with a 1-ampere current the process requires about 120 hours, and with a 4-ampere current about 30 hours. The completion of formation is indicated by the formed plates gassing freely, but this indication has to be interpreted somewhat carefully and in the light of experience.

As elsewhere insisted on, only pure "brimstone" sulphuric acid should be used in the above processes, and only distilled water employed for its dilution.

III.—COMPLETE CELLS

Having described the construction of several typical + and − plates, we can now proceed to show how these and the necessary fittings are assembled to form a complete cell, and what additional safeguards are introduced to meet the practical requirements of efficient service.

Important Details. Before dealing with particular cells it may be well to schedule a few points on which anyone examining an unfamiliar pattern of secondary cell for the first time should focus his attention. The following schedule, however, should not be regarded as exhaustive :—

(i.) The facility with which the plates and the condition of the cell can be inspected.

(ii.) The suitability of the containing vessel for the required service and the facilities for testing by hydrometer or otherwise the condition of the electrolyte and for renewing or changing the electrolyte.

(iii.) The methods by which all the plates of the same kind (+ or −) in a cell are paralleled so as to form electrically one large plate. Upon the details of this method will depend to a great extent the even distribution of the current over the surface of the plates, resulting in uniform current density all over individual plates and throughout the cell.

(iv.) The method of leading the current into and out of the cell and connecting the cell in series with the adjoining cell on either side. Incidentally the modification, if any, for terminal or regulating "end cells."

(v.) The separators, if any, used to prevent buckling, treeing, and short-circuiting generally, and the probable effect of such separators on the internal resistance of the cell and the current distribution on the plates.

(vi.) The screens, if any, used to minimise the spraying of acid when the cells are "gassing" freely.

Separators.—There is one detail with reference to which a few general and preliminary remarks may tend towards conciseness. One of the difficulties met with in secondary cells arises from the closeness with which, for electrical reasons explained elsewhere, the "+" and "−" plates are packed together. It is obviously essential that no solid conductor should, inside the cell, bridge the short distance between plates of opposite polarities, as such bridging would short-circuit the plates, cause the discharge of the cell under severely adverse conditions, and make it impossible to recharge it.

The chief faults by which the separating space may be bridged are by the buckling of the plates, by "treeing," or by sufficiently big pieces of active material becoming detached from a plate and falling across and bridging the space.

The tendency to buckle has always been a difficulty in the design of lead secondary cells, and it is aggravated during periods of heavy discharge or charge. It has been greatly minimised by careful design of the supporting lead frameworks on both sides, but this alone is not sufficient, and therefore there is often inserted between the opposed plates some form of solid *insulating* "separator," whose function is to keep them apart by a mechanical obstruction.

The separator used may either be in the form of insulating rods or strips introduced at intervals, or may be a continuous diaphragm covering the whole surface of the plate. The separators of the former type commonly used are either (i.) *ebonite forks*, the prongs of which are pushed down between the plates or (ii.) glass rods or tubes of the necessary external diameter.

Such discontinuous separators, whilst counteracting the tendency to buckle, obviously do not safeguard short-circuiting by loose pellets of active material or by "treeing," which may sometimes occur through a metallic bridge growing out by electrolytic action from the negative plate. These faults may, however, be effectively safeguarded by solid diaphragms, which must, of course, be porous, as in primary cells, so as not to break the continuity of the liquid electrolyte. Various materials have been tried, such as unglazed porcelain, perforated sheets of celluloid, etc. The material now chiefly used is a thin sheet of wood which has been chemically treated so as to remove all harmful impurities. This treatment leaves the wood more porous than in its natural state, so much so that it is sometimes asserted that its introduction has no effect on the internal resistance of the cell, the increase of the resistance being one of the chief objections to the use of a porous diaphragm.

In some cases the wooden separators are very thin, being only of veneer thickness; they are then used in conjunction with glass tubes which give better insulation, whilst the thin continuous sheet of wood safeguards the other dangers.

One of the wooden separators used by the D. P. Battery Company is shown in Fig. 1,055. The wood is of veneer thickness, about 0·06 inch and in this instance is ribbed, the ribs being a little over half an inch apart A further example is given later in Fig. 1,059.

Fig. 1,055.—"D. P." Wooden Separator.

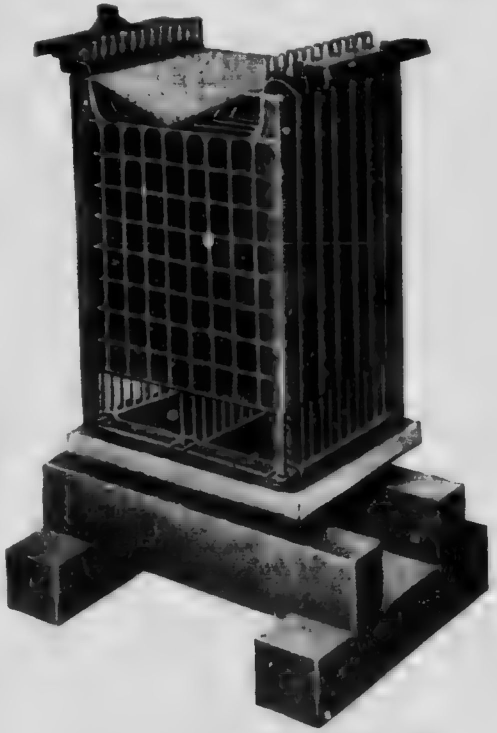
It is curious to note how each manufacturer using wooden diaphragms asserts that his process for removing the harmful constituents of the wood is unique and successful, his clients being cautioned against the use of wood which has not been properly treated. From this the conclusion may be drawn that it is important, and not altogether easy, to remove these constituents.

Lugs and Connecting Bars.—Not less important than the separators are the connectors which parallel the +ve and the −ve plates respectively in each cell, as has been explained in Vol. I. (*see* page 213), and is also further referred to in paragraphs (iii.) and (iv.) of the summary on page 1030 above. The connection is made by special lugs cast with the framework of the plate, these lugs being burnt to connecting bars as shown in the illustrations of complete cells given below.

Two general methods of joining up the cells for a large battery are in use. In the first the cells are placed (*see* Fig. 1,060) with the planes of the plates at right angles to the line of cells. In this method the connecting bars are lengthened and shaped, usually by turning the ends up vertically, so that the + bar of one cell can be connected to the −ve of the next, the cells being faced round alternately in opposite directions.

In the other method the cells are turned a quarter round so that the plane of the plates (*see* Fig. 1,062) is in the direction of the line of cells. The connecting bars then lie transversely between successive cells, and the +ve lugs of all the cells in one row are turned in the same direction—*e.g.* to the right. The appropriate lugs are then burnt to the connecting bar after the cells are in their final position, this method being used for the large and heavy cells. Electrically, the method has the advantage that the current flows straight across from, say, the + plate of one cell to the corresponding — plate or plates of the next without having to flow laterally to any appreciable extent along the connecting bar. The external resistance of the connections from cell to cell is thus reduced to a minimum.

It will be noticed that lugs are required for another purpose, namely, to suspend the plates in the containing boxes. For small cells the same lugs serve both for mechanical supports and as conductors to the connectors. In large plates, however, there are both supporting and connecting lugs, as may be seen in the peculiarly shaped lugs on the larger plates of the Pritchett and Gold and Electrical Power Storage Company illustrated in Figs. 1,038 and 1,053. The same may be noted also in other plates (*see* Figs. 1,040, 1,041 and 1,050). When large wooden boxes are used these supporting lugs do not rest upon the edge of the box, but on large sheets of tough glass ¼ inch to ⅜ inch thick, set on edge and resting on lead strips laid on the bottom of the box.



[illegible] D. P. [illegible]

A few examples only of complete cells are given here, as, in order to avoid repetition, it is more convenient to deal with certain types of cells in connection with their utilisation. Cells designed for some special purposes are described in the next section (pages 1037 to 1042), and the reader is further referred to the section on "Secondary Batteries in Sub-stations" (*see* pages 1271 to 1294).

The D. P. Accumulator.—The standard types of cell made by the D. P. Battery Company of Bakewell, Derbyshire, are shown in Figs. 1,056 and 1,057. In these cells the separators consist of wooden rods arranged in a frame as shown and supporting wooden diaphragms; but alternatively glass tube separators can be supplied. The cell shown in Fig. 1,056 is

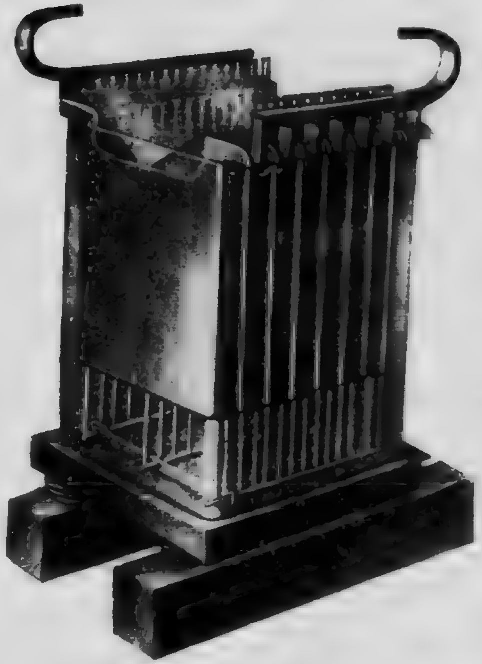


Fig. 1,057.—The D. P. Accumulator for Smaller Currents.

known as the "L S" type, and illustrates the construction used for heavy currents; whilst Fig. 1,057 is the "L" type, with smaller plates of a lower capacity per plate and used for smaller currents. Thus the normal charging rate for the L S cells is 20 amperes per + plate, whilst the corresponding rate for the L cells is 8 amperes.

The Chloride Accumulator.—The standard cell of the Chloride Electrical Storage Company, Limited, is shown in Fig. 1,058. Five + plates (*see* Fig. 1,041) and six − plates (*see* Fig. 1,050) are assembled, each set being cast to a massive bar with a lug, as shown, to form a + and a − group, which can then be introduced into a glass, a lead-lined wood, or a metal box. The special lugs by which the plates are supported upon the upper edges of the box as distinct from the conducting lug on each plate through which the current flows can be seen more distinctly in Figs. 1,041 and 1,050. A glass box is shown in Fig. 1,058. It is of such a depth that when the plates are suspended by their lugs from the top edges of the cell ample space is provided beneath the plates for the deposit of sediment for a long period, thus saving labour in cleaning out the cells.

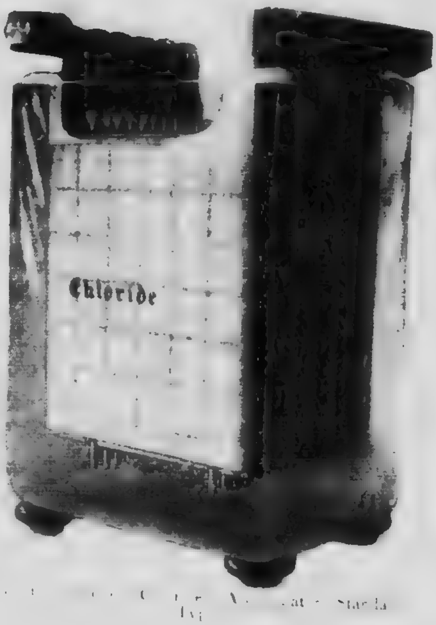


Fig. 1,058.—The Chloride Accumulator: Standard Type.

This is one of the accumulators

in which a thin sheet of wood of the exact size of the plates is used as a separator, for the reasons and with the precautions explained above. The wooden sheet is supported by two wooden rods which are suspended from the top of the plate by indiarubber rings as shown in Fig. 1,059. The ends of these rods can be clearly seen in Fig. 1,058. It is claimed for these separators that the chemical treatment of the wood has been so effective that no change can be detected in its appearance or composition, even after it has been in use, and therefore in continual contact with acid, for many years.

Fig. 1,059.—Wooden Separator used in "Chloride" Cells.

The "Plantide" cell made by the same firm is very similar, but uses the "Plantide" plates described on page 1021 as + .

The Hart Accumulator.—The standard cell of the Hart Accumulator Company is shown in Fig. 1,060, in which appear three cells joined up in series. This also is one of the cells in which wooden separators are used, and these can be clearly made out on the figure as well as other details referred to in the summary on page 1030.

A feature of these cells is the non-corrosive terminal, of which an enlarged view is given in Fig. 1,061. Special [illegible] shaped as shown are burnt to the + and — electrodes of the cells and [illegible]

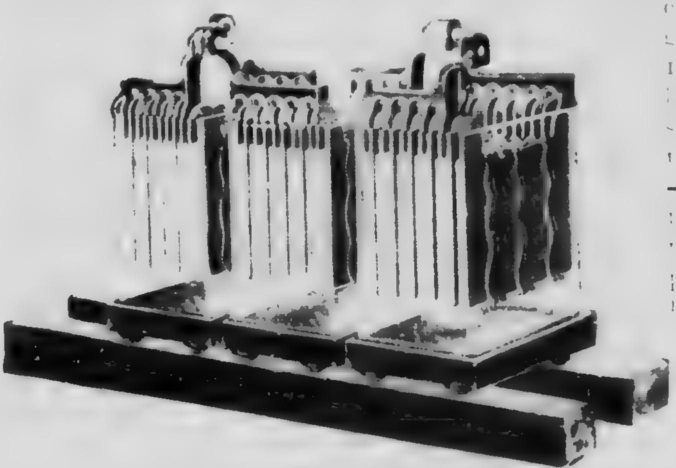
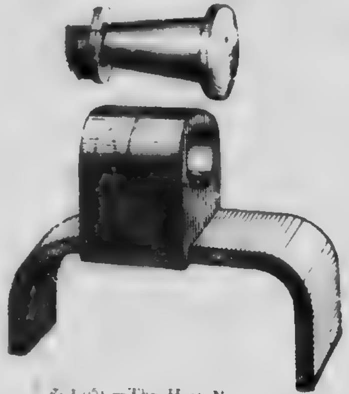


Fig. 1,060.—The Hart [illegible]

antimonial lead, and the surfaces of contact are carefully trued up. In fitting two cells together for the first time a brass replica of the bolt is used to enable a much greater pressure to be attained than would be possible with a bolt and nut in the softer lead material. When the joint has been tightened up in this way the brass replica is slacked and removed and its place taken by the lead bolt and nut, which, being of the same material as the electrodes, cannot give rise to electrolytic corrosion. Another advantage of the device is that it is impossible to couple up the cells wrongly, because the + terminal carries one half of the taper and the — terminal the other half. If, therefore, the wrong terminals were brought together for coupling, the operation could not be completed without the mistake being discovered, and the danger of accidental reversal is thus well safeguarded.

Each cell is carried in a wooden tray, containing sawdust, which is supported on glass insulators as described at pages 213 and 214 of Vol. I. For the smaller sizes indiarubber discs placed on top of the insulators are used instead of trays.



g. 1,051.—The Hart Non-corrosive Terminal.

Other Complete Cells.—It would be easy to illustrate and describe other well-known cells, but the above will suffice for the present. Additional illustrations of complete cells will be found in the Secondary Battery section of the Chapter on Sub-stations (see pages 1271 *et seq.*).

Use of Special Boxes.—In the preceding illustrations of various types of cells the containing box shown has usually been of glass. Not only for purposes of illustration, but also in actual practice such boxes are convenient, because of their transparency, as they enable the condition of the plates to be more or less readily inspected without disturbing them. Further, although glass is brittle, it is a fairly stiff and strong material, is not acted on by the acid used, and, if properly annealed, is only cracked or broken by percussive blows. It is, moreover, comparatively light. For large sizes, however, glass is expensive, for its cost rises more rapidly than the size as measured by the cubic contents, and, moreover, large glass boxes are difficult to handle [illegible]. There are also certain applications in which glass boxes [illegible] broken somewhat easily, and for which, therefore, some [illegible] containing vessel must be devised.

The alternatives adopted are, as a rule, either lead-lined wooden boxes or [illegible] boxes, though occasionally other materials have been used [illegible] [illegible], which is expensive, and therefore chiefly employed [illegible]

Illustrations and, in some cases, descriptions of the various kinds of boxes used, will be found in the sections on "Cells for Special Purposes" (*infra*), and on the use of "Secondary Batteries in Generating and Substations" (*loc. cit.*). We therefore only illustrate here in Fig. 1,062 one example of heavy cells in lead-lined wooden boxes. These are the 35 plate "L" type

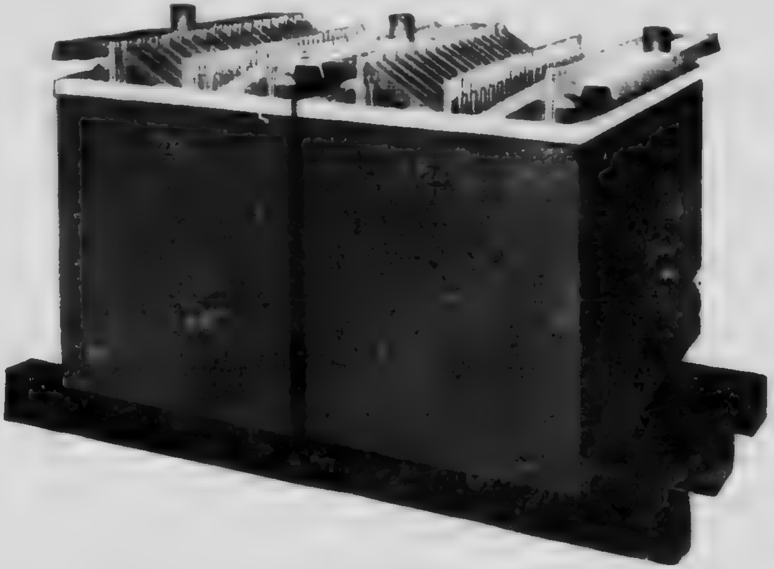


Fig. 1,062.—[illegible] Wood Boxes.

of cell, manufactured by The Pritchett and Gold and Electrical Power Storage Company. The complete cell weighs 1,5[illegible]0 lb. or nearly 14 cwt., measures 2[illegible] by 35½ inches, and stands 30¾ inches high from the wooden supports to the top of the [illegible]. Of this vertical height, however, only 15¾ inches are occupied by the active surface of the plates, which are 15[illegible] inches long.

CELLS FOR SPECIAL PURPOSES

The more important lead secondary cells described in this chapter are those which are chiefly used in large power schemes in generating and sub-stations, and generally in the electric distribution of power and for electric lighting, public and domestic. There are, in addition, other uses for secondary cells in which the demand is sufficiently great to warrant the production of a special type of cell which, while in principle the same as the [illegible]

[illegible]

[illegible] electric [illegible] of traction [illegible] the propulsion of road vehicles [illegible]

[illegible]

applications. It is proposed to deal very briefly with cells suitable for one or two of these purposes, the others being dealt with elsewhere.

Train-lighting Cells. The conditions of service, both mechanical and electrical, on board a train require a cell of more robust construction than the ordinary type described above.

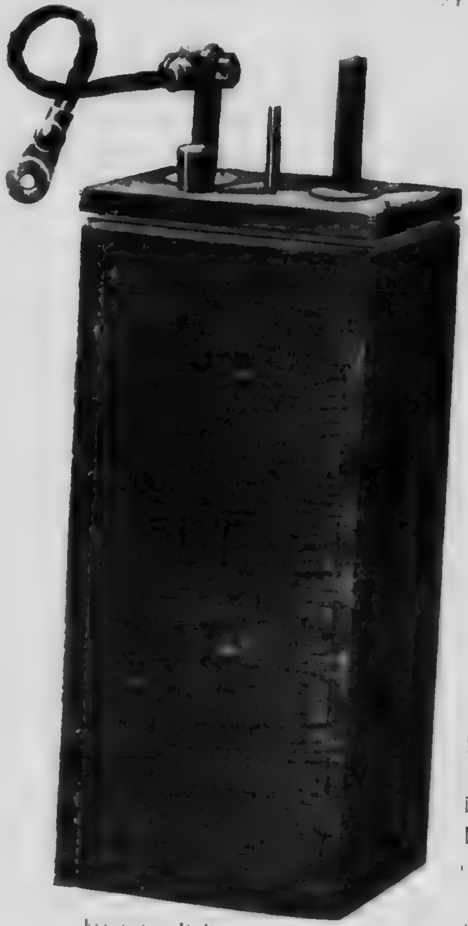
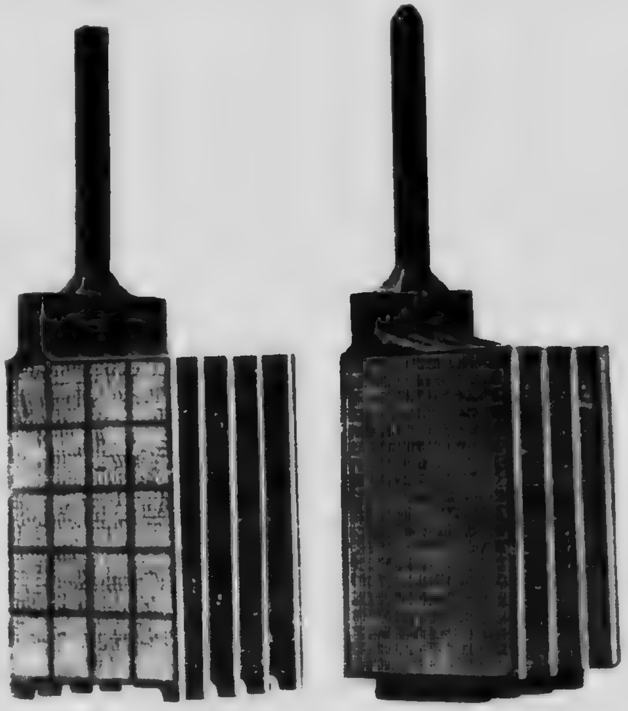


Fig. 1,003.—D. P. [illegible]

For instance, the jolting and swaying of the train require the cell to be so designed that it will stand mechanical shocks and so that the acid cannot be jerked out. Closed, though not hermetically sealed, cells in lead-lined wooden boxes are therefore usually employed, such as the one which is shown in Fig. 1,003, which gives an external view of a standard train-lighting cell manufactured by the "D. P." Battery Company. The outer case is a dove-tailed wooden box which is lined with thin (4-lb.) lead, the joints being autonomously soldered. The plates are insulated from the lead lining by vertical sheets of ebonite. When in use the lid is bolted down to prevent the splashing of the acid; openings are provided for the introduction, without taking off the lid, of a float to test the level of the electrolyte and of a hydrometer to measure its density.

Electrically also, the cell has to be constructed to stand hard usage. It may sometimes be accidentally overcharged, and at others starved or even totally discharged, as when a carriage cleaner forgets to switch off the lights. As the dead weight is of little consequence, the plates are therefore massive for both mechanical and electrical reasons, as may be gathered from Figs. 1,004 and 1,005, which depict the "−" and "+" sections respectively of the cell shown in Fig. 1,003. Except for being more substantial, these plates are constructed similarly to the standard type of the same company's "−" and "+" plates already described on pages 1028 and 1025.

They are pasted —ive and Planté +ive, and measure 5½ inches by 8½ inches, the —ive being 7 mm. thick and the +ive 9 mm. thick. The lugs of the separate plates and the paralleling rods of the section are exceptionally massive, as are the terminal lugs, which are 1 inch by ¾ inch. The latter, it will be noticed, are longer than in cells for general purposes, the object being to keep the upper surface of the electrolyte well below the level of the lid to minimise splashing over.



— S[illegible] [illegible] + [illegible]

[illegible]

Wood separators, such as are described elsewhere, are used, and the sections rest on the set of wooden blocks, shown in Fig. 1000, lying on the bottom of the box. It should be noticed that the resting lugs are differently placed on the + and — plates, thus minimising the danger of short circuit from masses of fallen sediment bridging the space between a + and a — plate.

[illegible]

The cell illustrated has seventeen plates and a capacity of [illegible] ampere-hours. These cells, when placed under a railway coach, need only be examined at long intervals for the purpose of adding water as required. It is claimed that they may remain in service for two or three years without being opened [illegible] and [illegible]. [illegible] that some of our leading railway companies [illegible] secondary cells in service thus freed [illegible] adding [illegible] appreciated as tending to economy of upkeep.

Ship Lighting.—For lighting on ships and yachts the conditions are similar to, though not so severe as for, train lighting. The special cells are therefore designed on much the same lines, as may be gathered from an inspection of Fig. 1,067, which illustrates a ship-lighting cell as made by the Hart Accumulator Company, whose plates have been referred to on pages 1023 and 1029. The side of the cell is cut away to show the construction, which should be compared with that of the cell just described above. The chief mechanical difference is that the plates do not rest on the bottom of the box, where there is the clear space usual in stationary cells. Instead, they are supported by means of the usual projecting lugs near the top of the plate on substantial wooden supports introduced at the two ends of the box. Ebonite separators appear to be used between the plates.

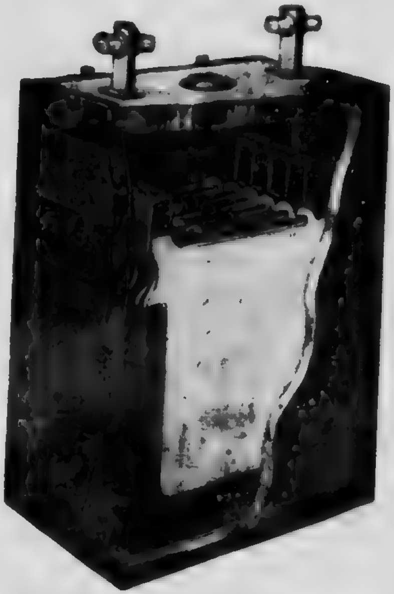
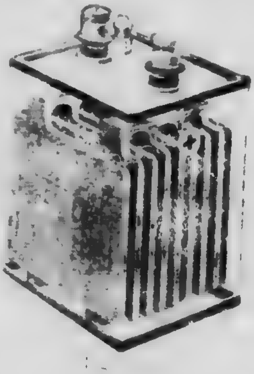
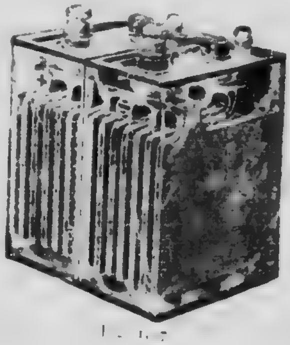


Fig. 1,067.—Hart Cell for Ship Lighting and other Purposes

Small Special Cells and Batteries. For the circuits of the sparking plugs of petrol motors on automobiles the custom is to use a small magneto-generator, with the details of which we are not concerned here, or a small 4-volt to 12-volt secondary battery whose discharge rate may be anything from a fraction of an ampere up to [illegible] amperes or more. The conditions can be satisfied by quite small cells assembled in two-cell to six-cell batteries.

[illegible]


[illegible]


[illegible]

[illegible] conditions are similar to the conditions [illegible] lighting [illegible], but the smallness of the output and the handiness of the necessary cells [illegible] many of the difficulties of satisfying them to disappear. By somewhat increasing the size and capacity the same battery may be [illegible]. There are numerous other uses for these and even smaller cells.

Ignition and Car-lighting Cells. From a number of excellent cells available a series of typical cells, as made by the Hart Accumulator Company, are illustrated in Figs. 1068, to 1070. Details of the + and − plates made by this firm have already been given, and therefore it will probably be most convenient to tabulate the statistical information regarding these cells as follows:

TABLE X.—DATA [illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	W[illegible]
[illegible] 1,068	1	[illegible]3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1[illegible] lbs.
1,069	2	5[illegible]	[illegible]	[illegible]	4	[illegible]	[illegible]	[illegible] lb
1[illegible]	[illegible]	4[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20¼ lb

The batteries are contained in strong celluloid boxes with sealed lids and non-corrosive terminals; there is also a vent plug in each cell to provide for the escape of the electrolytic gases during charging. They are supplied in teak crates or in metal or teak boxes provided with handles for portability, and with the terminals brought to the outside. These portable batteries are standardised up to 12 volts and 100 ampere-hour capacity with a maximum discharge current of 15 amperes.

Hig[illegible] [illegible] ing B[illegible]. As a final example of small secondary cells for a special, [illegible] useful, purpose, Fig. 1071 shows a set of fifteen cells in glass boxes mounted on a wooden block about [illegible]0 inches long, also made by the Hart Accumulator Company. Each cell consists of two plates only, rather widely separated, and the lug of the + of one cell is burnt into the lug of the − of the adjacent cell. The two can be together lifted out of their respective cells, a device employed many years ago in telegraphy for the zincs and coppers of primary batteries in series. The figure represents one element of a

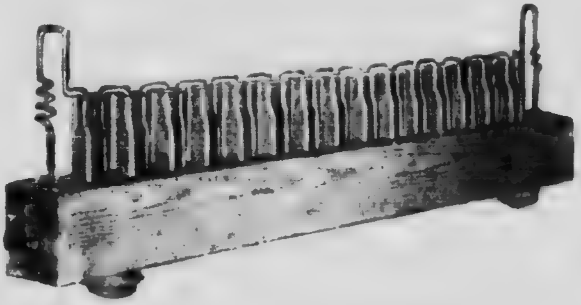
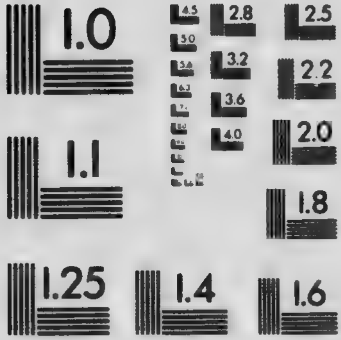


Fig. 1071.—[illegible]

MICROCOPY RESOLUTION TEST CHART

(ANSI and ISO TEST CHART No. 2)



APPLIED IMAGE Inc
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Rochester, New York 14609 USA
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(716) 288 - 5989 - Fax

high-voltage battery for testing work. The element will give from 33 to 35 volts on open circuit, and batteries up to 500 volts or more can be set up by assembling a sufficient number of elements, though insulation must be carefully attended to, each element being placed on two glass insulators of the usual pattern (*see* page 214, Vol. I.). The current obtainable is, of course, quite small, the normal rate of discharge being 0·05 to 0·1 ampere, though 0·2 ampere can be obtained if required.

V.—THE WORKING OF LEAD SECONDARY CELLS

In this section on the "working" and in the next following section on the "care" of lead secondary cells, attention is chiefly directed to the individual cell. The treatment and regulation of groups of lead secondary cells or "batteries" is reserved for Chapter XII. on "Sub-stations" in connection with the utilisation of the cells for engineering purposes.

The lead secondary cell, being primarily a piece of chemical apparatus in which the various chemical materials at different times assume more or less unstable and sometimes deleterious combinations, often sensitive to the physical conditions of temperature, mechanical vibration, etc., it follows that in the case of such apparatus considerations have to be kept continually in mind quite different from those which are important in the care and maintenance of moving machinery or other electrical apparatus. It would require a treatise to enter minutely into all the varied cases which may arise, and to describe the treatment proper in every possible contingency.

Very much, however, depends upon the way in which the battery is used as a source of energy whilst under discharge, and as an absorber of energy during charge. This, again, is closely related to the assumed capacity of the battery as a storehouse for energy, and also as a source for the supply of electricity or of electric energy. In other words, the *kilowatt-hour* storage capacity and the *coulomb* or the *ampere-hour* output, which should be regarded as its maximum discharge before being recharged should be approximately known. This raises questions as to the proper rating of cells, which, being fairly simple, may be considered first, especially in connection with an examination of the general electrical behaviour of the lead cell during charge and discharge.

Rating of Cells.—The quantity of electricity in kilo-coulombs or in ampere-hours[*] which can be safely taken from a fully charged lead secondary cell depends upon the rate of discharge, and would be greatest at a very low rate. As this quantity forms a convenient method for rating the cell, it is obvious that for clearness a standard time of discharge must be agreed upon. A practice has thus grown up of rating the capacity of the cell on the total quantity in coulombs which it can safely discharge under a steady current maintained for *ten hours*. If this current be exceeded the battery

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One ampere-hour = 3,600 coulombs = 3·6 kilo-coulombs.

will be more quickly discharged, but with a diminished output, and it is important to know for how long such a heavier discharge may be taken.

The following table bearing on these points is compiled from figures supplied by the Electrical Power Storage Company :

TABLE XI.—DISCHARGE OF LEAD SECONDARY CELL

Duration of Discharge	Capacity in Terms of 10-Hour Discharge	Current in Terms of 10-Hour Current	Average [illegible]	[illegible]
Hours.			V	
10	1·000	1·000	1·97	1·83
9	·979	1·088	1·97	1·83
8	·950	1·187	1·96	1·83
7	·918	1·311	1·96	1·83
6	·879	1·465	1·95	1·83
5	·833	1·667	1·94	1·83
4	·782	1·954	1·93	1·8
3	·717	2·389	1·91	1·80
2	·633	3·167	1·89	1·78
1	·500	5·000	1·87	1·75
0·75	·448	5·835	1·85	1·70
0·5	·373	7·450	1·83	1·70
0·25	·208	8·330	1·80	1·7
Peak		12·500	1·76	1·60

The information contained in the table is plotted graphically in the curves in Figs. 1,072 and 1,073. In Fig. 1,072 the discharge current for different periods of discharge, from one to ten hours, is plotted against those periods as a base. The result is given in curve A. Though the rate rises as the time falls, the product of the two also diminishes, showing a falling off in the capacity for heavy current discharges. Had the capacity not been affected by the rate of discharge, the curve would have been the dotted curve B, which is plotted to a constant product of 1,000. The increasing interval between the two curves as the time of discharge diminishes should be noted.

Another way of exhibiting the same results based upon the figures in the table is given in Fig. 1,073, in which the capacity as a fraction of the ten-hour capacity is plotted against the same base as in Fig. 1,072. This capacity is given in column (2) and is obtained by multiplying the figures in column (1) and (3) in the table and dividing by 10. The inset curve on the right continues the other curve downwards so far as a one-minute discharge to the same scale of capacity, but to a more open scale of time. The results are interesting ; for instance, for a five-minute discharge the capacity falls to 8·5 per cent. of the ten-hour capacity.

The maximum emergency discharge rate of 12·5 times the ten-hour rate is given in the table as a guide in specifying batteries for equalising purposes when operating on circuits subject to violent and rapid fluctuations, the inset curve in Fig. 1,073 being also intended for the same purpose.

The other point, which is of importance to the user of a lead secondary battery, is the P.D. per cell which can be obtained from the battery for the different rates of discharge dealt with in Table XI. This P.D. depends, by Ohm's law, on both the E.M.F. and the resistance of the battery, and would be smaller for the higher rates of discharge even if the E.M.F. remained constant, because although the resistance is very low, it is not negligible, since in the complete battery the resistance of the connections, as well as the real internal resistance of each cell, must be taken into account. The effect of resistance does not account for the whole or even the greater part of the drop in P.D., and therefore it follows that the E.M.F. is also changing, as might be expected.

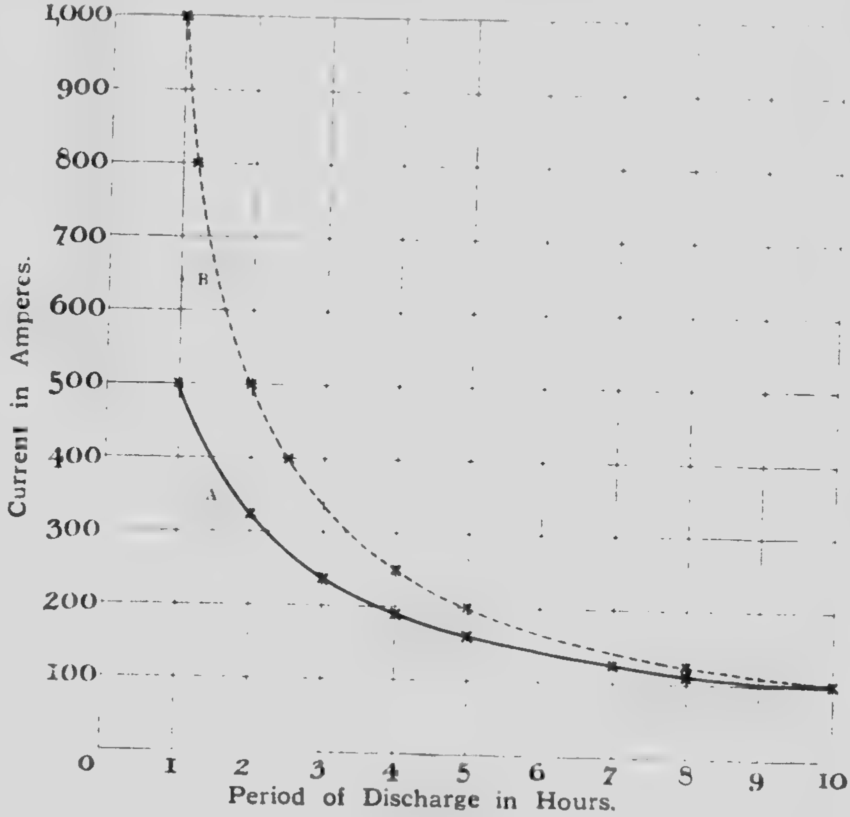

Fig. 1,072.—Steady Currents for Different Periods of Discharge.

Discharge Curves.—The table gives the average and the final P.D.S., but it is necessary to have more detailed information, and this is given in the curves in Figs. 1,074 and 1,075. In these curves—which are six in umber —the base is the time measured from the commencement of the discharge to its close, the current being kept constant at the value given in the table for the full period of discharge. The curves in Fig. 1,074 are for 10-, 7-, and 5-hour rates respectively, and the curves in Fig. 1,075 plotted to a more open time-scale are for the 3-, 2-, and 1-hour rates. The curves, as regards their general and relative shapes, are representative curves for lead batteries, but the actual values of the voltage in a given case depends upon the temperature and condition of the battery. The curves must therefore only be taken as a general guide.

The general shape of the curves is that they appear to be made up of three different portions, the boundaries between which are not at all definite, and become more indefinite as the period of discharge is diminished. These are (i.) a starting period during which the drop is somewhat rapid; (ii.) a period during which the P.D. falls quite gradually, and which extends over the greater part of the period of dis-

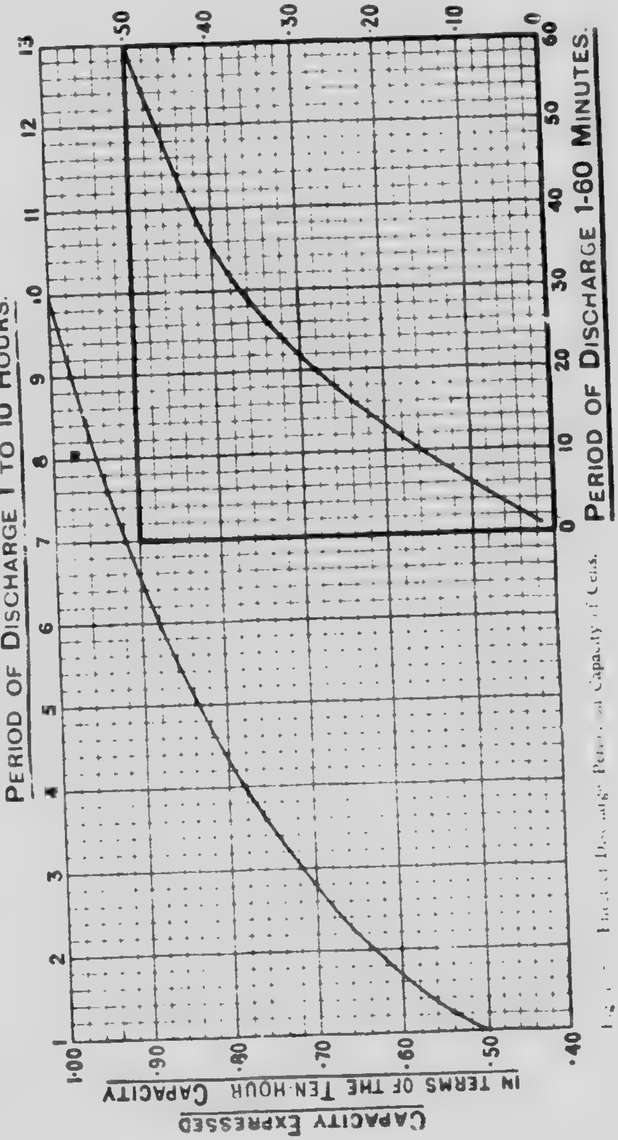

Fig. [illegible] Effect of Discharge Period on Capacity of Cells.

charge for slow discharges; and (iii.) a final period during which the P.D. falls with increasing rapidity to a limiting value. In all sections the rate of fall increases with the rapidity of the discharge, and any theory of the action of the cell must account for these changes.

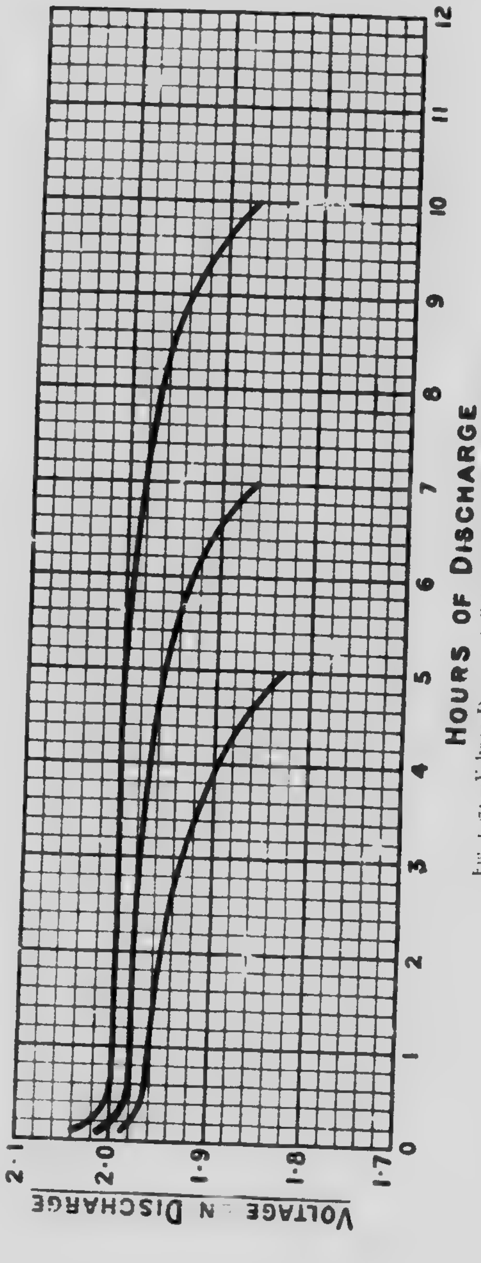

Fig. 1,074.—Voltage Drop per Cell for Different Discharge Periods.

Charge Curves.—A knowledge of the P.D. per cell of a battery whilst being charged is also of importance to the user, but here again only average or representative figures can be given, as the actual values depend not only on the rate of charge, but also on the condition and temperature of the battery. The curves given in Fig. 1,076 are from data supplied for average conditions by the Electrical Power Storage Company. One curve, A A A, is for the normal or best rate of charge, which should be completed in about eight hours, and the other, B B B, is for the maximum rate, which should be completed in not less than $4\frac{1}{2}$ to 5 hours; a higher rate of charge would injure the battery. In charging, the resistance of the battery increases the necessary P.D., but here again the chief differences are due to increases in the back E.M.F. The curves again appear to divide into three positions, which merge into one another, and are the converse of the corresponding portions of the discharge curves. The final rise at the end of the charging period is, however, much more rapid, and covers a greater difference of P.D. than the corresponding fall at the end of the discharge.

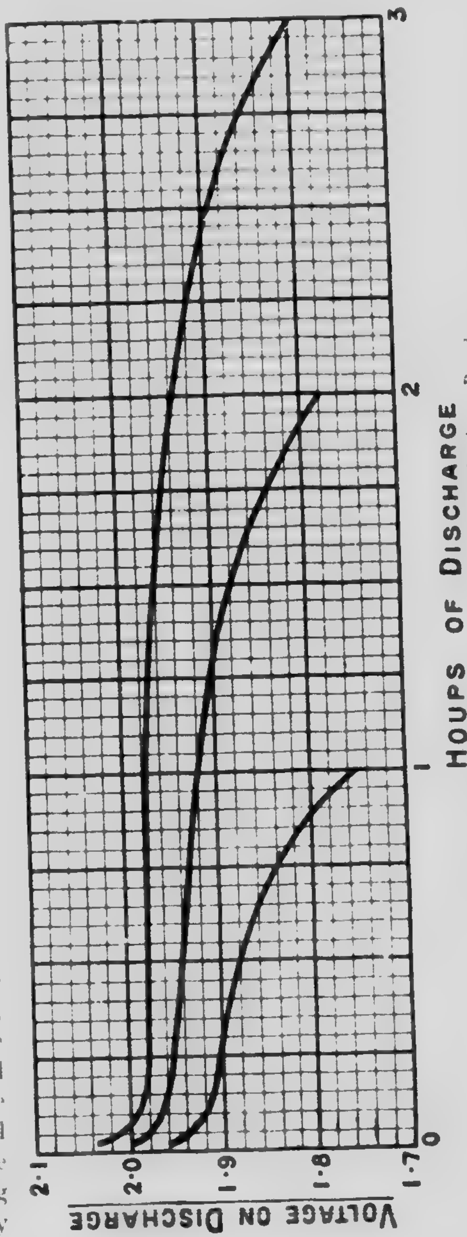

Fig. 1075. Voltage Drop per Cell for Different Short Discharge Periods.

Efficiency.—The efficiency of a secondary battery—that is, the ratio of the energy taken out to the energy put in—is not so easily determined as in most of the other cases of transformation of energy which occur in electrical engineering. The disturbing factor, which may and often does vitiate the data obtained from a single experiment or even a series of experiments, is the impossibility of estimating the state of the battery as regards the energy stored at any period and more especially at the end of a discharge. With a generator or a motor or a kinetic or a static transformer, we know that at the beginning of an experiment, before the current is switched on, the machine or apparatus has no store of energy upon which it can draw during the experiment. Further, when the experiment is over and the currents are switched off, the machine or apparatus does not retain in an available form any of the energy which has been given to it during the experiment. Not so, however, with a secondary battery. The energy between charge and discharge is retained in the battery as energy of chemical separation, and no means have yet been devised of measuring this stored energy directly under the complex conditions of working. We neither know what energy previously stored in the battery we may be able to draw upon when we start, or how much of this original energy or of the energy we have put in during the experiment may be left behind when we finish.

Under these circumstances to obtain even approximately accurate results a large number of charges and discharges should be taken, every precaution being used to insure that the condition of the battery shall be kept as constant as possible. There is, of course, no difficulty about measuring during experiments the actual input and output in watt-hours, either by wattmeters or otherwise.

These points being kept in view, the Electrical Power Storage Company gives as efficiencies which it is prepared to guarantee, the values which appear in Table XII.

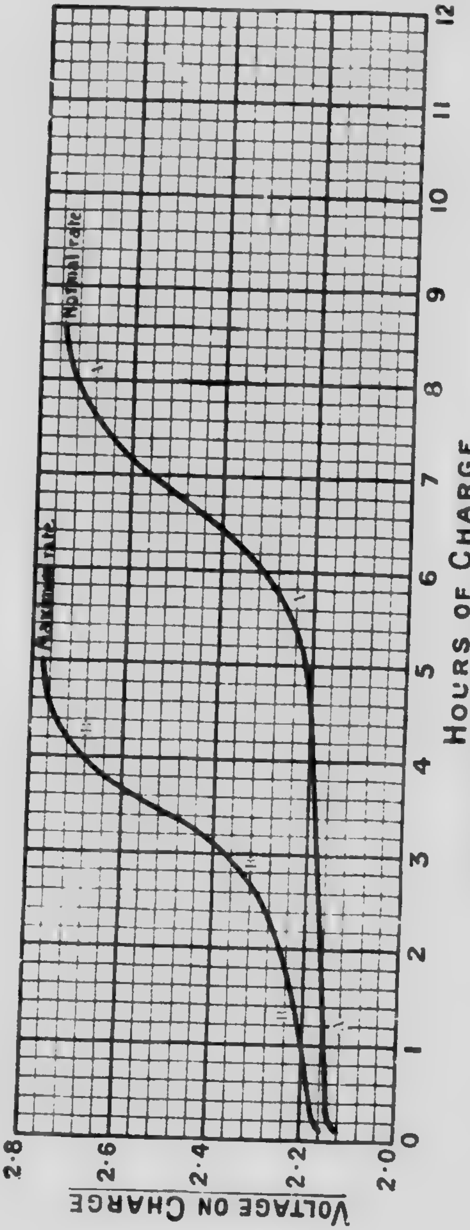

Fig. [illegible] of Voltage per Cell for Normal and Maximum Rates of Charge

TABLE XII.—EFFICIENCIES OF SECONDARY CELLS

[illegible] Hours.	Energy Efficiency per cent.
10	75
[illegible]	74
5	73
3	72
1	7[illegible]

As might be expected from the curves already given, the efficiency depends upon the period of discharge. In each case, as in the preceding curves, charge and discharge are with steady currents, the discharge being th the proper current for the period named and the charge being with normal charging current.

The efficiency in any given case depends upon many other factors an the rates of charging and discharging. To consider each separately would be tedious, but mention may be made of the effect upon the ciency of the size of the plates, the efficiency being distinctly lower r large than for small plates. The figures in Table XIII. are given by the Chloride Electrical Storage Company for a battery of the Planté type in good condition equipped with wood separators and working at 60° F.

TABLE XIII.—EFFICIENCY AS AFFECTED BY SIZE OF PLATE

Size of Plates	[illegible]	[illegible] ½ Hours	[illegible] Hours	2 Hours	1 Hour
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Under 400 sq. ins.	75	75	74	[illegible]	70
400 to 600 sq. ins. ...	74	73	72	71	68
Over 600 sq. ins.	73	72	70	69	66

The working method of obtaining the efficiency under varying conditions of charge and discharge is by the use either of wattmeters or of ammeters and voltmeters. Recording instruments are to be preferred, and if wattmeters are used it is desirable to have two instruments, one of which only records when the battery is being charged and the other when it is being discharged. Such instruments can be arranged to work quite automatically on fluctuating loads.

Quantity or Ampere-hour Efficiency. Information very useful in working the battery can be obtained from records of the quantities of electricity dealt with in the charges and discharges. The ratio of the total quantity, as measured in ampere-hours, of the *output* to the similar quantity of the *input* is usually referred to as the *ampere-hour efficiency*, and in a well-cared-for secondary battery may be expected to be of the order of 90 per cent. This ratio is obviously not an *efficiency* in the engineering sense of the term, as the quantities measured have by themselves no monetary value, but are only factors in the energy which the engineer buys and sells. The measurement of the ratio is subject to the same difficulties as have been referred to above in the case of the real efficiency, and similar precautions must be taken, the results being open to similar criticisms. Coulomb-meters or time-integrating ammeters are suitable instruments for the measurements.

VI.—ELEMENTARY THEORY OF THE LEAD SECONDARY CELL

The fundamental scientific principles upon which the working of all secondary cells or accumulators depend have been fully explained in Vol. I. (*see* pages 200 to 215). In addition, the curves given (Figs. 1,072 to 1,076) in the last section show in a general way the electrical results of the application of these principles in the case of the lead accumulator. Any complete theory should, of course, account for the peculiarities indicated by the curves, but the problem is an exceedingly complex one from the chemical point of view, and cannot be said to have been fully worked out even yet, after many years of research This is due partly to the complexity of the chemical compounds, which may be present on each of the plates at a particular period of charge or discharge. Thus, whilst the initial and final states of the bulk of the active material on the plates and of the electrolyte is sufficient to explain the main actions on well-known lines, the other compounds present, both solid and liquid, are not without influence, and give rise, in fact, to some of the marked peculiarities. Without going into great and what might be wearisome detail, we can only indicate the general course of the chief or resultant changes.

As more than once explained in the preceding pages, every accumulator stores not electrical but chemical energy, and is essentially a piece of chemical apparatus, capable of transforming electrical into chemical energy and vice versa. Some knowledge of chemistry must therefore be assumed in the following paragraphs.

The chemical theory of the action of the cell, which in its broad lines is widely accepted though still subjected to criticism in certain details, was worked out by Gladstone and Tribe in 1881 and 1882, and is founded upon actual analyses of the materials used and whilst in use. It is known as the "double sulphation theory," and instead of assuming that the chemical effect of the current is to electrolyse water, H_2O, it regards the sulphuric acid H_2SO_4, as the active electrolyte, decomposed by the action of the current into the Faradaic ions H_2 and SO_4.

The chief chemical results of the formation and initial charging of the battery are the production of surface layers of what is technically known as "active material" on the + ' and − ' plates. On the + ' plate as already explained, this material is lead peroxide (PbO_2), a chocolate-coloured solid which gives the + ' plate its characteristic colour, whilst on the − ' plate the active material is spongy lead, which is merely metallic lead in a state of fine division. It has the dull appearance of the metal, but is of a somewhat lighter grey colour owing to an admixture of white lead sulphate. Metallic lead grids or plates form the mechanical backing and the electrical conductors behind the active material on both plates. The electrolyte is dilute sulphuric acid, the separate ions of which are the kathion, hydrogen (H_2), and the anion, sulphion (SO_4).

Theory of the Discharge. Starting with this distribution of chemicals, which satisfies all the conditions necessary for a voltaic cell (see page 151, Vol. I.), the chemical actions on discharge (during which the + plate is the electro-negative element or kathode and the − plate the electro-positive element or anode) may, on the double sulphation theory, be represented thus:—

Positive plate: $PbO_2 + [H_2]^* + H_2SO_4 = PbSO_4 + 2H_2O$ . . (1)
Negative plate: $Pb + [SO_4] = PbSO_4$ . . . . (2)

The total action at the + plate, summarised by equation (1) is, in all probability, partly due to the action of the electrolytic hydrogen and partly to ordinary chemical action. From this point of view lead oxide (PbO) would be formed by the action of the hydrogen, and be immediately converted into lead sulphate by the neighbouring sulphuric acid, thus:

$$PbO_2 + [H_2] = PbO + H_2O \quad . \quad . \quad . \quad . \quad . \quad (1a)$$
$$PbO + H_2SO_4 = PbSO_4 + H_2O \quad . \quad . \quad . \quad . \quad . \quad (1b)$$

The net result is that lead sulphate ($PbSO_4$) is formed on both plates, and sulphuric acid disappears from the solution. The decrease of the density of the solution due to this disappearance of sulphuric acid is a well-known fact, and is used as a test to determine the approximate state of the cell with reference to its charge. A curve for a particular case is given below (Fig. 1.077).

This theory, however, whilst explaining the main changes during discharge, does not account for the shape of the various discharge curves given in Figs. 1.073 to 1.075. If it were the whole explanation the curves should be nearly horizontal lines for the whole period of discharge, and when all active material has been converted into lead sulphate on both sides, the E.M.F. would disappear, and the P.D. drop to zero quite suddenly.

There is, however, the well-known apparent recuperation of the cell during intervals of rest which is shown in Fig. 1.077, taken from an article † by Mr. Hibbert in the "Encyclopædia Britannica." The P.D. of the cell during discharge is given by the curve marked A, B, C, D, which in the parts A and B is similar to curves already given. The discharge was continuous at a constant current of 10 amperes, except that at the points C and D it was stopped for a short time to extract samples. During the period of rest at C the P.D., which had fallen to 1·85 volts, rose to 1·95 volts, and it took more than half an hour of further discharge to bring it down to 1·85 volts. Although the fall between these voltages was much more rapid than before the break, the result shows an increase in the energy and the ampere-hours given to the discharge circuit. Similar but more striking results are shown at D, where the cell had been discharged to a P.D. of 1·4 volts, that is much below the usual value at which in practice a discharge is stopped. During the few minutes stoppage the voltage rose, and on the resumption of the discharge the P.D. started at about 1·9 volts, and it was nearly half an hour before it again fell to 1·4 volts. Such recoveries during periods of rest are characteristic of the lead secondary cell and follow either a complete discharge or a partial discharge at a very rapid rate.

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* The square brackets [ ] in this and the following equations are used to denote *electrolytic ions.*
† *Encyclopædia Britannica*, 11th Edition (1910), Vol. I., "Accumulators."

It is obvious from the above that accompanying the main reactions, and perhaps as intermediate stages in them, there are one or more minor and/or secondary reactions sufficiently important to affect the result, and very little investigation is sufficient to reveal their presence, though it is not so easy to evaluate their relative importance. The fact is the whole phenomenon is very complicated and much of it obscure and it is only possible here to refer to one or two of the more important points.

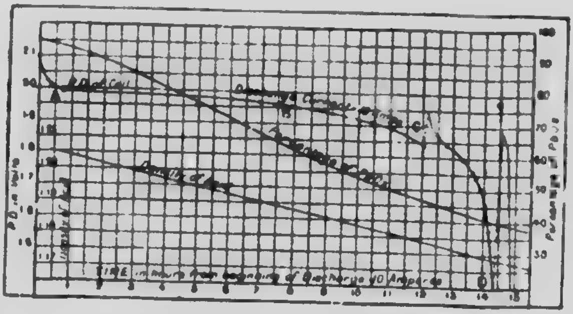

Fig. 1,077.—Recuperation of Discharged Cell during Rest.

In the first place, chemical analysis shows that with ordinary commercial plates only a small proportion of the active material is converted into lead sulphate at the time that the electrical measurements show that the cell is practically discharged. There still remains plenty of spongy lead on the — plate and of PbO_2 on the + . For instance, in the experiments dealt with in Fig. 1,077, the percentage of PbO_2 on the + plate was determined at different times during the discharge, and the curve drawn shows the results. At the end of the discharge there was still 38 per cent. of PbO_2 left. What probably happens is that the lead sulphate formed acts as a not very permeable screen between the electrolyte and the active material, and thus cuts down the terminal P.D. in two ways, one by interposing a high resistance in the circuit and the other and more effective by cutting down the E.M.F. at its source by temporarily keeping H_2SO_4 from the unact[illegible] on active material. If, however, the cell is allowed to rest, the screen is broken through slowly at innumerable points, diffusion proceeds, and the E.M.F. is restored, though an increase of resistance remains. This view would account for recuperation.

Much even of the gradual fall in the P.D. shown in comparatively slow discharges may be accounted for by changes in the composition of the electrolyte immediately surrounding the active materials. The effect of discharge, as we have seen, is that, on the whole, the electrolyte is weakened by desulphation. Whilst, however, the total weakening may not be great the desulphation up against the active material may be almost complete, and fresh H_2SO_4 can only reach the active material by the slow process of diffusion. Now the weakened acid has a higher specific resistance (*see* page 1055), and where H_2SO_4 disappears locally the E.M.F. ceases to exist. The question is one of average. We have a number of separate bits of the plates giving different E.M.F.s, probably down to zero, and of different specific resistance. It is as if we had a number of different small cells in parallel on each pair of plates. On consideration, it will be seen that this view accounts not only for the slope of the discharge curve but also for the increased slope of the heavier discharges in which the local rate of disappearance of H_2SO_4 is increased, making it more difficult for diffusion to keep pace with it, especially when further obstructed as indicated in the preceding paragraph.

In addition to the above there is often a certain amount of gaseous polarisation due to the liberation of hydrogen at the + plate and the formation of higher sulphates at the − plate, which tends to lower the available E.M.F. and therefore the P.D. These actions are especially prominent in heavy discharges.

The above by no means exhausts the minor actions which have been found to exist, but we cannot here, notwithstanding its interest, pursue the subject further.

Theory of the Recharge.—On *recharging* the + plate becomes the anode and the − the kathode, and the main result of the various actions is the decomposition of the lead sulphate on both plates, according to the following over-all equations:

Positive plate: $PbSO_4 + [SO_4] + 2H_2O = PbO_2 + 2H_2SO_4$ . . (3)
Negative plate: $PbSO_4 + [H_2] = Pb + H_2SO_4$ . . (4)

Here again the action at the + plate is more complicated than is shown in equation (3). It probably takes place in not fewer than two stages, in the first of which water, in the presence of lead sulphate, is decomposed by the − ion (SO_4), and in the second lead peroxide is formed as shown by the equations:—

$[SO_4] + 2(H_2O) = H_2SO_4 + 2(OH)$ . . . . . . (3a)
$2(OH) + PbSO_4 = H_2SO_4 + PbO_2$ . . . . . . (3b)

The main result shown in equations (3) and (4) is, as is necessary in a good commercial secondary battery, to restore, at least approximately, the condition of things which existed before the preceding discharge. The lead sulphate on the + plate is reconverted into lead peroxide, and that on the − is again reduced to spongy lead, whilst the electrolyte absorbs H_2SO_4, as shown by the curve in Fig. 1,078.

Complications, however, arise similar, *mutatis mutandis*, to those which occur during the period of discharge. The E.M.F. of the cell is now against the current, and rises as the charging proceeds; during the main period of charge this rise is sufficient to mask the advantage of the decreased resistance of the electrolyte due to its enrichment. Charging curves similar to the discharging curves of Fig. 1,077, and taken from the same article, are given in Fig. 1,078. They are for a charge with a constant current of 9 amperes, and show the effects of brief periods of rest at the points B and C. The curve shows a fall of P.D. on re-starting after a break, and the theory that diffusion is being delayed gives, as before, a simple explanation. During charge acid is being formed in the pores of the active material, and diffusion is from within outwards. The break gives time for diffusion to take place, and when the circuit is re-closed the back E.M.F. has fallen appreciably, and consequently a smaller P.D. is sufficient to start the charging current. The curve showing the rise of the percentage quantity of PbO_2 on the + plate should also be noted.

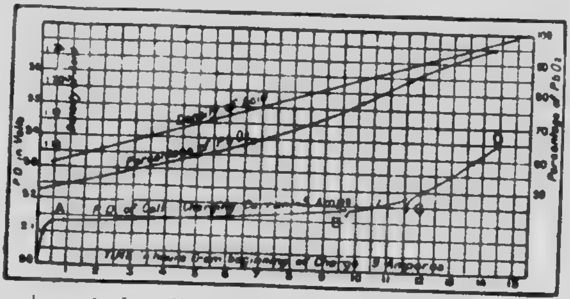

Fig. 1,078.—Loss of Voltage of a Cell under Charge during a Rest.

In addition, polarisation is caused by the evolution of hydrogen at the − plate and the formation of persulphuric acid ($H_2S_2O_8$) and hydrogen peroxide (H_2O_2) at the +. Towards the end of the recharge this polarisation increases rapidly and gas is liberated freely, external energy being available for this purpose. The final rise of the curve is therefore rapid, for the presence of the gas increases the resistance as well as the back E.M.F. It should always be remembered that the production of gas leads to waste of energy, as it is an irreversible process. Moreover, the bursting gas bubbles spray into the atmosphere a certain amount of sulphuric acid, and therefore tend to weaken the electrolyte permanently.

Resistance.—The resistance of a secondary cell from terminal to terminal is made up of the resistance of the solid material of the framework of the + and − plates, through which the current flows to and from the active material, the resistance of the active material including the contact resistance between solid and liquid and the resistance of the lectrolyte for the particular distribution of current set up.

The resistance of the liquid paths is so low, owing to the large sectional area and short length of the liquid, that every endeavour should be, and is, made to reduce the metallic resistance to a minimum, as even then, owing to the low conductivity of lead, it forms a very appreciable fraction of the whole resistance of the cell. The solid paths should therefore be as short and as stout as other considerations permit. The resistance of lead like other metallic elements, has a positive temperature coefficient of about 0·4 per cent. per 1° Centigrade.

The electrolyte, dilute sulphuric acid, has a specific resistance depending upon its concentration and upon its temperature. Concentrated sulphuric acid has a density nearly double that of water, and one effect of dilution is to diminish the density. Since, as described elsewhere, it is easy to test the specific gravity of the solution, it is convenient to use this density for specifying the state of the electrolyte. Now the curve connecting the specific resistance with the specific gravity of dilute sulphuric acid has a curious U shape with a minimum value of 1·3 ohms at 15° C. between specific gravities 1·22[illegible] and 1·230. Working specific gravities usually vary between 1·215* in a fully charged cell and 1·180* in a discharged cell, and therefore the resistance of the electrolyte increases as the cell becomes more and more discharged. The temperature coefficient, as in all electrolytes, is large and negative; that is, the resistance diminishes rapidly with rise of temperature, and this diminution is more than sufficient to mask the rise of metallic resistance in the supports. Thus a cell at 25° C. has only about half the resistance as the same cell at −7° C. It is therefore desirable to work the cells at or about 15° to 25° C.

The actual value of the resistance of any given cell depends upon the above considerations and upon its size, but is very much smaller than the resistance of a primary cell; in the case of small cells it is seldom more than a few thousandths of an ohm, and is much less in the case of large cells. There is, owing to complex causes, some of which have been mentioned above, a distinct rise of resistance towards the end of a charge or of a discharge.

Capacity and Output.—This subject has already been dealt with in a preceding section (*see* page 1042 *et seq.*) under the title "*Rating of Cells*," and the remarks then made may be reread in the light of the above theories.

In the section referred to we were dealing with the ordinary working conditions of batteries. In addition to the output being affected by the rate of discharge, it is also affected by temperature and by the method of charging (*e.g.* at constant P.D.). As regards temperature the output is increased by a rise of temperature, and appears to attain a maximum of a somewhat high temperature.

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* A [illegible] specific gravity 1·215, [illegible] F. [illegible] per [illegible] H_2SO_4 [illegible] specific gravity 1·18 contains 24·7[illegible] per cent.

The relations of the *capacity* to the *size and weight* of the plates is much more definite in Planté-formed than in pasted plates. Thus commercial Planté plates, by whatever process formed, have a capacity usually about 1 ampere-hour per 100 sq. cms. of surface, or 6 ampere-hours per 100 sq. ins. The limits are from one-half to double these values, but the figures given are very near the usual proportion. The output per pound weight will obviously depend on the character of the backing, and might be expected to have a much wider range. In practice, however, there are certain limitations, and the usual practice shows from 6 to 9 ampere-hours per pound for +ve for a 10-hour discharge rate. The output per pound weight for Planté —ve may be substantially higher.

With pasted plates the variations may be greater, and depend upon the ratio of the quantity of active material to the size and weight of the grid or frame. The output per pound may vary from 6 ampere-hours, where the active material weighs 20 per cent. of the total weight to 23 ampere hours where the proportion rises to 80 per cent. The output per unit surface of plate in these cases will obviously depend on the design.

VII.—THE CARE OF LEAD ACCUMULATORS

The lead secondary battery, or, as it is frequently called, the "lead accumulator," being a piece of chemical apparatus, the rules for its maintenance are chiefly influenced by chemical considerations rather than by considerations which are usually classified as engineering. The main aim is to keep the battery in such working order that the only changes in it are those produced by its regular discharge and recharge, so that at the end of each cycle the battery returns to its previous condition. The attainment of this ideal in actual practice is very difficult, if not impossible, and all that can be done is to approximate to it.

The first fact which has to be recognised is that, however carefully the battery has been manufactured, the different cells are not, from a chemical point of view, absolutely the same. Small variations, which cannot be avoided, creep in during the process of manufacture and affect the working of each cell, so that after a period more or less prolonged differences appear which can be ascertained by quite easy tests. The first essentials of good management are the regularity of the charging and discharging of the battery, and the necessity for being on the look out for the appearance of differences in the behaviour of the individual cells. It is therefore necessary that every cell should be examined periodically at brief intervals, say, once a fortnight or once a month at least.

Charging and Discharging. Where the load may fluctuate rapidly and violently, as in electric traction, rolling mills, etc., a secondary battery is seldom the sole source of supply, and should be protected by boosters or other automatic controllers of the charging and discharging currents. These are often not necessary on ordinary electric lighting and power supply circuits. In many such cases the charging current can usually be arranged to be given at a convenient time and at the voltage most suitable for the battery. On the other hand, the discharging current is not under such control, but has to be supplied as and when required by the consumers. It may vary from a very low current to a current which, for a short period, may even be destructive. There may also be intervals of rest when the battery is quite idle, and experience has shown that such intervals, if prolonged, do not conduce to the preservation of the battery in good working order.

In this connection it would be well to consider the effects of persistent over-charging or of insufficient re-charging, whether due to carelessness or unavoidable.

Over-charging.—Speaking quite generally, the effects of over-charging are not only that energy is wasted in the production of electrolytic gases which escape, and whose chemical energy therefore cannot be returned to the circuit, and which also weaken the electrolyte, but that it also tends to deteriorate plates.

The effect is different upon the $+$ and the $-$ plates. On the $+$ plate too prolonged a charge at a low rate produces excess of active material which eats into the backing. On the other hand, if the cell is over-charged at a high rate, the active material is disintegrated, falls off the plates, and is thus put out of action.

At the $-$ plate the result of over-charging is to cause either contraction or expansion of the active material, according to its composition and previous treatment ; in either case, the result is to damage the plate permanently.

At both plates, the effect of continuing the charge until the cells are "gassing" vigorously is to waste energy.

Insufficient Charging.—Persistent insufficient charging in successive cycles will obviously lead to a lower specific gravity of the electrolyte owing to the non-reduction of a portion of the lead sulphate during each cycle. At each charge the plates will be injuriously affected, and on account of the corresponding over-discharge an abnormal amount of material will be disintegrated and fall to the bottom of the cells. To bring the plates, if possible, back into condition they should be subjected to a prolonged charging at a very low rate. This may save the cells if the periods of insufficient charge have not been too long continued.

Ordinary Charging.—With the battery in good condition, a usual working rule as to charging is to give 10 per cent. more ampere-hours than the amount taken out in the previous discharge. The rule, however, is somewhat crude and must be used with care, as the amount of recharge required obviously must depend on the character as well as the quantity of the previous discharge. Even when applied the battery should periodically—say, every sixth or seventh charge—be well charged irrespective of the previous ampere-hour readings, and until all the conditions of a full charge are attained. If the battery is completely resting it should be given a freshening-up period at least once a fortnight; and if, during the preceding fortnight, there have been small discharges, the freshening-up period should be correspondingly prolonged.

The *first charge* of a newly erected battery should always be given under the supervision of or in strict accordance with definite instructions received from the manufacturers.

Ordinary Discharge.—This is usually considered complete when the P.D. of the battery has fallen to an average voltage of, say 1·8 volts per cell, or ($1·8 \times n$) volts, where n is the number of cells on the battery. The real controlling voltage, however, should be E, the E.M.F. of the battery, whose connection with V, the P.D. voltage, is given by the familiar equation:—

$$V = E - RC$$

Thus the value of V for a definite value of E depends on the current C, and notwithstanding the low value of the battery resistance R is appreciably different for small and large currents. Moreover, the rise of R towards the end of a discharge tends to accentuate the point. In this connection the discharge curves in Figs. 1,073, 1,074, and 1,075 should be carefully studied.

An ingenious instrument indicating automatically the permissible final value of V for varying values of C has been designed by Mr. R. Rankin, and will be found described in *The Electrician*, Vol. LXXIII., page 449, for June 19th, 1914.

The automatic regulation of secondary batteries on rapidly fluctuating loads is dealt with in connection with sub-station working (*see* Chapter XII).

Periodical Examination.—This should take the form of (i.) a careful inspection of the visible condition of each cell and its plates; (ii.) a test of the voltage of each cell; and (iii.) a test of the specific gravity of the electrolyte in each cell. For tests (ii.) and (iii.) convenient instruments have been specially designed for secondary cell work.

Inspection.—The points to be noted are:—

(*a*) The level of the electrolyte, which should never be allowed to fall below the top of the plates. The causes which influence this level are detailed later.

(*b*) The colour of the plates, more especially the +s, which should be of a good chocolate colour and not either light brown or of a very dark, nearly black, chocolate colour. On the − the spongy lead should be of the familiar grey type and not of a dark slate colour.

(c) The absence of abnormal "sulphation," which is distinguishable from the normal sulphation by the much whiter appearance of the plates. The whiter sulphate is non-conductive, and can only be broken up (if at all) by the expenditure of an excessive amount of energy in the charging current.

(d) The flatness of the plates, which should show no signs of bulging or buckling.

(e) The absence of contacts between the + and − plates caused by flakes of scale bridging the narrow gap. Such flakes should be carefully removed as soon as observed.

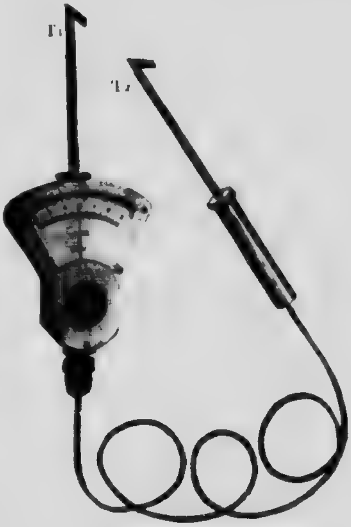

Fig. 1,079. Cell-testing Voltmeter.

Voltage Tests.—A neat pattern of voltmeter, constructed by Messrs. Evershed and Vignoles, for cell testing, is shown in Fig. 1,079. It is of the moving coil type, described at page 718, Vol. I., and is designed to be held in the palm of the hand, contact being made by the spike terminal T_1 fixed on the instrument and by the hand-spike T_2, which forms the second terminal. The instrument can be used in any position, and the pivots upon which the moving coil rotates are very strongly constructed, and are claimed to be "undamageable." The scale is graduated from 0 to 3 volts in one-tenths on each side of a central zero. A record block can be clamped to the instrument, leaving the scale exposed and is convenient for entering the readings as made.

Another pattern, as made by the General Electric Company, of London is shown in Fig. 1,080. It is also of the moving coil type, and fitted with special terminals, one T_1 below the instrument, and the other T_2 at the end of a flexible insulated wire, sufficiently long to reach to the other terminal of the cell, when T_1 is resting against one terminal. For single-cell testing the scale reads from 0 to 3 volts, and is divided into one-twentieths of a volt.

Specific-gravity Tests. Another test, which should be periodically and can be rapidly applied, is the testing of the specific gravity of the solution of each cell by means of a constant-weight hydrometer of special pattern. As the hydrometer, which is shown in Fig. 1081, should float in the space between the plates without touching either plate, it is made with a flat reservoir and thin stem. It is direct reading, with an open scale usually extending from 1·075 at the top to 1·300 at the bottom. The condition, that it must float clear of the plates when a reading is being taken, must be carefully observed, as otherwise the reading will not indicate the specific gravity and will be misleading.

Another method is to use specific gravity beads enclosed in a thin glass reservoir, as shown in Fig. 1,082. The reservoir has openings at the top and bottom, so that when it is immersed in the space between the plates it is filled with the liquid there, and is emptied again when drawn out. The beads are of different colours and of different average densities, and in a particular test some may float up to the top and others remain at the bottom, but one bead will usually be found in some intermediate position, and this bead indicates the approximate specific gravity. The method is free from some of the uncertainties of the other method, but as the number of beads is obviously limited it can only give approximate results. Where four beads as shown are used the densities are, as a rule, 1·150, 1·170, 1·190, and 1·210; with three beads the densities are usually 1·170, 1·185 and 1·200.

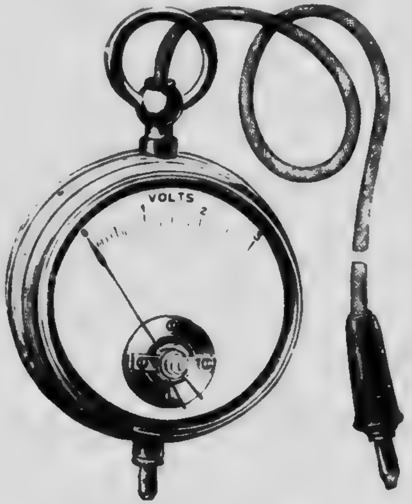

Fig. 1,080.—Cell-testing Voltmeter.

Condition of the Electrolyte.—In the regular working of the battery the dilute sulphuric acid, which constitutes the electrolyte, receives additions of H_2SO_4 during charge, and is impoverished during discharge (*see* pages 1051 to 1054). The condition at any time is ascertained by the specific gravity tests described above. In ideal working, the acid lost during discharge should be fully restored on the succeeding recharge, and the average concentration of the electrolyte should therefore remain unchanged. This result is not easily ensured, since the concentration of the electrolyte is affected by other causes.

In the first place, evaporation is always going on, but leads to loss of water only and not of sulphuric acid. It therefore tends to concentrate the electrolyte. On the other hand, the electrolyte is impoverished by loss of acid when the plates are gassing, in which case the bubbles of gas rising to the surface burst there and spray acid into the atmosphere. Spray arresters of sheet glass are used to counteract this. Acid is also lost when parts of the active material flake off and lead sulphate is carried to the bottom of the cell in an insoluble form, and also when strong acid, as sometimes happens, is imprisoned in the pores of the active material.

The remedy for natural evaporation is to introduce *distilled* water to bring up the working level to the proper position. The water, though added carefully so as not to disturb the sediment at the bottom, should be well mixed with the electrolyte, and not simply poured in so as to float on the top of the denser liquid. A good plan is to introduce this "topping up" water near the bottom of the plates by means of a glass or ebonite tube. To replace losses pure acid of specific gravity not greater than 1·300 or 1·400 should be added, and care should again be taken that the new liquid is thoroughly mixed with the old.

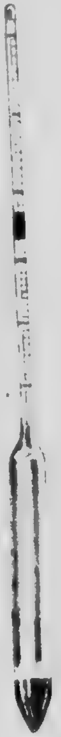

Fig. 1.

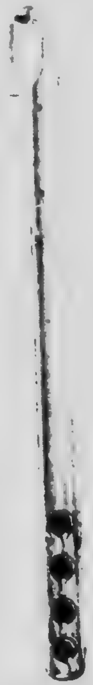

Fig. 2.

Hydrometers for Cell Testing.

Fluctuations of the level of the electrolyte affect the exposed parts by the different chemical actions of sulphation and peroxidation, which may take place as they are alternately submerged and exposed to the atmosphere. This leads to a rotting of the lugs if these only are subjected to variable exposure, but if portions of the plates are exposed the uncovered part of the + will be corroded and that of the − will become inactive. The obvious remedy is to keep the level of the electrolyte as constant as possible and not to allow it to fall far before replenishing the liquid.

Every individual defective cell must be attended to promptly and carefully. If badly sulphated it will gas heavily long before it is fully charged and give a high voltmeter reading, the electrolyte at the same time becoming "milky" in appearance. The remedy is to give it extra charging by means of a booster, or to disconnect it from the battery during one or more discharges, the battery circuit being maintained intact by a "jumper" or bridging conductor.

Cleanliness.—Cleanliness in its widest sense—that is, the protection of the cells from the introduction of *any* deleterious impurities—is essential to the successful working of a lead secondary battery.

It has been already mentioned that only *distilled water* should be used for making good the losses due to evaporation, and where there is a large battery, it may be economical to instal special distilling plant.

Loss of acid must be made good by the addition of *pure sulphuric acid*, diluted as mentioned. The presence of chlorine, nitrates, acetates, or organic substances, any of which may be found in commercial acid, will injuriously influence the forming action of the charging current. Other common impurities in commercial acid are arsenic, iron, copper, and mercury, which tend to disintegrate the active material during discharge.

Another source of impurities is *the atmosphere* to which the cells are exposed and which, in certain localities, may lead to serious trouble owing to the settling down of solid impurities on the cells, or to the absorption by the electrolyte of deleterious gases. Such gases as chlorine, ammonia, or sulphuretted hydrogen, though not usually present in dangerous quantities, may occur in certain parts of the country, and any one of these will cause trouble in the battery, the effects being cumulative. The air admitted to the battery room in such localities should therefore be carefully purified. Solid particles of iron or of oxides of calcium and magnesium may occur in the neighbourhood of iron works, and other dangerous impurities in other localities. In all such localities the air of the battery room should be purified by filtration or otherwise.

Effects of Temperature.—In a tropical country careful attention must be given to the effects of the increased average temperature and of excessive variations of temperature. For instance, with regard to the specific gravity of the acid, for which the general direction is that it should not exceed 1·215, it must be remembered that if the acid has this specific gravity at 100° F., it will have a specific gravity of about 1·228 at 60° F., the specific gravity increasing about 0·001 for every 3° F. reduction in temperature. Moreover, when warm the acid is chemically more active, and therefore the battery will require more charging to counteract the greater tendency to sulphation.

Low temperature does not seriously affect the working of a lead secondary battery, but simply reduces the capacity for the time being. High temperature, on the other hand, tends to destroy the battery by disintegration of the -|- , and by making it possible to over-work the battery owing to its increased capacity.

Overhauling.—It is very desirable that from time to time a lead secondary battery should be thoroughly overhauled and cleaned out, the plates being removed from the cells and washed, and the electrolyte renewed so far as is necessary. The frequency of such overhauling will depend upon the work and care of the battery, and once a year may be regarded as desirable under ordinary circumstances.

The work should be done either under the direct supervision of, or according to instructions received from, the manufacturers of the particular battery, and it would probably be misleading if we were to describe in detail any particular method here. For our purpose it is sufficient to indicate that such periodical overhauling is necessary.

Similar remarks as to specific instructions apply if it be necessary to put the battery completely out of service for a prolonged period for instance, during a long summer vacation

Renewals. Notwithstanding careful and well-directed maintenance, including periodical inspection at short intervals and periodical overhauling at longer intervals, the individual plates of a lead secondary battery sooner or later either fall to pieces or otherwise become inefficient, and require to be replaced if the battery is to continue to be effectively used. This exhaustion of the plates occurs sooner with the + than with the −, and at one time it was the rule to regard the useful life of the latter as twice that of the former. The fact is so well recognised that "upkeep" contracts, starting from the date of the first installation and including the renewal of the plates in whole or in part, are frequently arranged, especially by private users, with the manufacturers who supply the battery. The annual premiums are fairly heavy, and bear testimony to the seriousness of the risk. The following notes briefly indicate the considerations which should be kept in view in renewing or dealing with defective plates.

If some of the plates of the + or − section of a cell have so deteriorated that it is desirable to renew them, the whole section should be renewed, and not merely the defective plates.

Positive plates can be used so long as they will hold together and are not buckled to any serious extent, their capacity probably being not much below the ordinary maximum.

Negative plates lose their capacity by the hardening of the active material or by its disintegration, and when the capacity has fallen so low that it tends to deteriorate the + plates by an excessive amount of charging, the − plates should be replaced.

If new + are fitted to old − the possible reduced efficiency of the latter will require them to have more charging than should be given to the positives, which are therefore over-charged and subjected to abnormal wear and tear.

Much the same thing happens if new − are fitted to old +, as the latter are then liable to be over-worked and to deteriorate rapidly.

Buckled plates need not necessarily be renewed, but should be attended to as soon as possible. No attempt should, however, be made to straighten them if they are, as is probable, otherwise defective until they have been brought into a healthy condition, which can be effected by prolonged charging at about half the normal rate, care being taken first to ensure that there are no internal contacts. Contacts due to buckling can be removed by carefully forcing the plates apart by temporary separators of ebonite or other suitable material. After the plates are restored to a good healthy condition they can be straightened by pressure, carefully applied after inserting clean wooden blocks of the correct thickness between them.

VIII. THE NICKEL-IRON SECONDARY CELL

As remarked elsewhere, one of the greatest drawbacks of the lead secondary cell is its great weight per unit of energy stored. This is due partly to the density of lead, the principal material used, and partly to its low tensile strength and stiffness, which makes it necessary, for mechanical reasons, to use fairly massive frames and supports for the active material. If some of the stronger metals—such as steel, nickel, cobalt, etc.—could be employed, then quite apart from the lower density of the metal a much smaller volume could be used for the supports.

Possible Secondary Cells. The industrial importance of the problem has attracted the attention of many inventors, and it may be recalled that, as described in our historical section (*see* pages 202 *et seq.*, Vol. I.), the earliest secondary batteries from 1803 till Planté's researches about 1860 were not lead batteries. Even the great success of the lead secondary cell, as developed by Planté and Faure, rather stimulated than otherwise the search for other practical combinations, amongst which the attempts to replace the spongy lead − by zinc were the most numerous and persistent. On discharge the − plate becomes the + element in the cell, and the substitution of the more electro-positive zinc for lead raises the E.M.F. to about 2·5 volts at the commencement of discharge, falling to about 2·2 volts at the end. This raising of the cell voltage is a substantial advantage, but unfortunately certain practical difficulties—chiefly due to local action—have not yet been overcome. The reduction of weight per watt-hour output is considerable.

Another development which has been industriously followed up is the substitution of an alkaline electrolyte such as potassium hydrate (KOH) for sulphuric acid. This renders possible other materials for the plates, and of those available the combination—

Zinc—Potassium hydrate—Copper oxide

has attracted most attention. Unfortunately the E.M.F. of the combination is only about 0·8 volt, and therefore, although the ampere-hour output for a given weight is much in excess of that of an ordinary lead or even of the "zinc-lead peroxide" combination referred to above, the low E.M.F. reduces what may be called the "weight efficiency" to much the same level as the last-named cells. The advantages of an alkaline electrolyte are great and much work has therefore been done in the direction of searching for metallic combinations which, with such an electrolyte, would produce a practicable secondary cell.

Edison's Researches.—No inventor has worked at this problem with such persistence and unremitting toil as Mr. T. A. Edison, who since 1901, or earlier, practically devoted himself to finding a solution, and worked quietly for several years without publishing results, except for a premature publication in 1903. About 1908 a practical cell was evolved which has since been improved in details as the result of further experiment and of experience gained in the working.

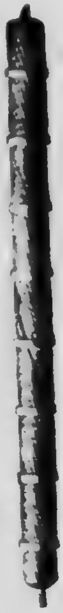

Fig. 1,083.—The + Tube of the Edison Storage Cell.

In this cell the metals used are nickel and iron, the active + material being nickel hydrate (NiH_2O_2) on the + plate, and the active — material iron oxide (FeO) on the — plate. The electrolyte is a 21 per cent. solution of potassium hydrate (KOH), to which has been added a small amount of lithium hydrate (LiOH), the addition of the latter being found to improve the action of the cell, though it does not enter into the main theory. With these materials the action is based on the oxidation and reduction of metals in an electrolyte which does not combine with and will not dissolve either the metals or their oxides, and which, although decomposed by the action of the cell, is at once reformed in equal quantity, and is therefore a constant solution not changing in conductivity or density. Such a combination is ideal from both the chemical and the practical point of view if only the energy stored per unit weight be a practicable quantity.

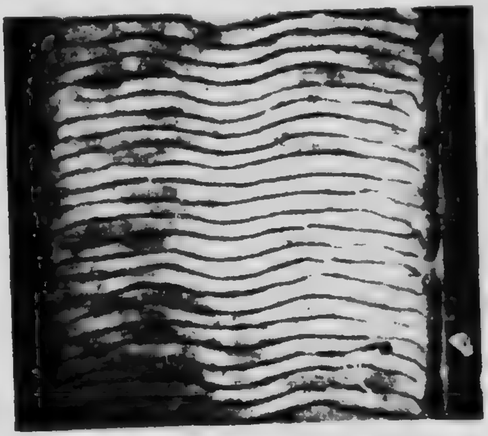

Fig. 1,084.—Sections of Laminations in Loaded + Tube Magnified 3 Diameters.

Formation of + .—The active material NiH_2O_2 is thrown down as an apple-green precipitate when a solution of a nickel salt is heated with potash or soda. It dissolves in ammonia with a blue colour, but separates out again as a crystalline powder when the solution is boiled. The process by which the nickel hydrate used in the cell is prepared has not been published.

This material is packed into perforated tubes made of nickel-plated steel. These tubes, one of which is shown in Fig. 1,083, are manufactured from perforated ribbon, which is turned by a special machine into the form of a closed spiral ¼ inch in diameter with a double-lapped seam. This tubing, cut into 4⅛-inch lengths, is placed in a machine which loads the active material into the tube in very thin layers, placing between each two layers a thinner layer of pure nickel to improve the conductivity and to ensure good electrical contact between the remotest active material and the tube. After each flake of metal is inserted a weighted ramrod falls on it by gravity, and as this operation is repeated about 300 times for each tube the contents are pounded into a compact mass consisting of this number of distinct layers of each material. The degree of lamination thus obtained is well shown in Fig. 1,084, which is a sectional view of a loaded tube magnified eight times. Eight small seamless nickel-plated steel rings (Fig. 1,083) are slipped over each tube about ½ inch apart to give it rigidity and strength to resist the forces developed by the expansion of the active material during charge, an expansion which caused trouble in the earlier patterns.

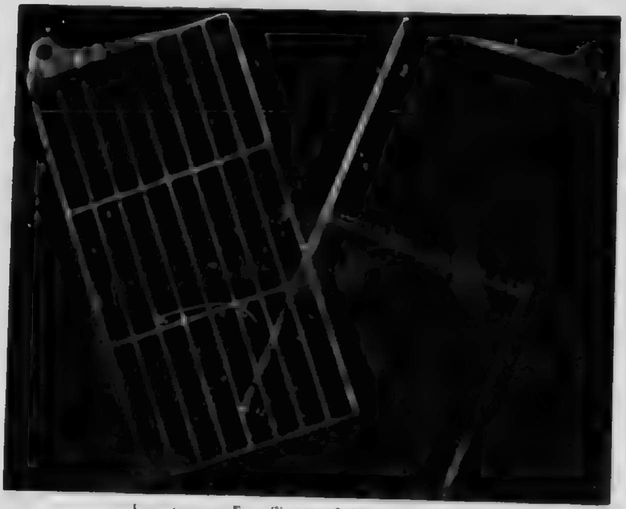

Fig. 1,085. Two Types of Supporting Grids.

The tubes are pinched flat at both ends to form suitable terminals for clamping into the steel grid seen on the right-hand side of Fig. 1,085, which is a steel punching so slit along the horizontal edges that the tube terminals are inserted between individual clamping jaws, and the clamping operation is completed under great hydraulic pressure. The finished plate is shown about quarter full size linearly in Fig. 1,086. It may be

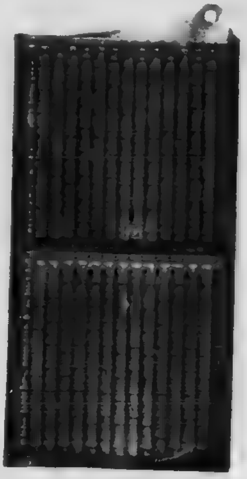

Fig. 1,086. [illegible] Plate.

oted that in order to pack the tubes into the smallest possible space the nding rings are alternately at different distances from the ends.

Formation of — The active material (iron oxide) for the negative lates is also contained in tubes made of nickel-plated steel, but, instead of being circular, these tubes re rectangular in section, as hown in Fig. 1,087. They are herefore more of the shape of pockets than tubes, and are sually so described. Each pocket is about ½ inch wide by 3 inches ng and a little over ⅛ inch thick. The iron oxide active material is ixed, before loading, with a very small percentage of mercury, which s it increases the conductivity, performs a function similar to that of the re nickel discs on the + tube. The pockets are loaded in a tamping achine similar to the one used for the tubes, and the loaded pockets are subjected to additional pressure in a machine which also slightly crimps the edges, so that they fit neatly into the interstices of the — grid. This grid, seen on the left-hand side of Fig. 1,085, is also a punching of nickel plated steel, and when all the pockets are in place the whole plate is subjected to hydraulic pressure, which squeezes the pockets into intimate

Fig. 1,087.—Rectangular — Tube

Fig. 1,088.—Edison — Plate

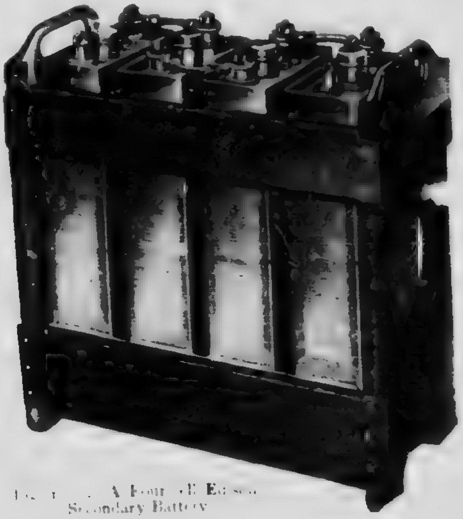

Fig. [illegible].—A Four-cell Edison Secondary Battery

ontact with the grid, corrugates the surface, increasing the strength and compresses the active material into hard solid cakes. The finished plate is shown in Fig. 1,088.

The sizes given above both for + and — have reference to what

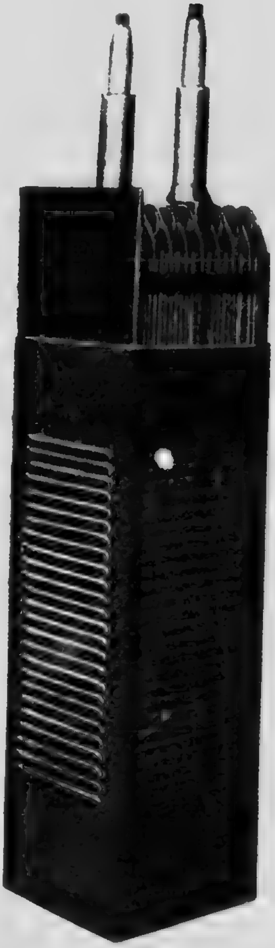

Fig. 1,090.—Edison Cell with Plates partly raised.

are known as "Type A" cells, intended primaril for use on electric vehicles. A smaller size know as "Type B," and used for petrol-car igniti and lighting, is made in the same manner.

The appearance of the completed cell ca be seen in Fig. 1,089, which shows a batter of four cells joined up and placed in a woode frame for portability. A single cell with its plates partly drawn out of the containing cas is shown in Fig. 1,090. The outer case, which is made of nickel-plated steel, is describ below. The plates without the case, but assembled together and ready for insertion in the containing box, are shown in Fig. 1,091. The prope number of plates of each kind to give the required capacity are mounted on a steel rod, t which a steel tapered pole is attached at right angles, as shown in Fig. 1,092, which is a view seen from above of the top of a cell with th cover removed. The plates are spaced b washers of the proper width, and finally a lock washer and a nut are placed on each end of the rod.

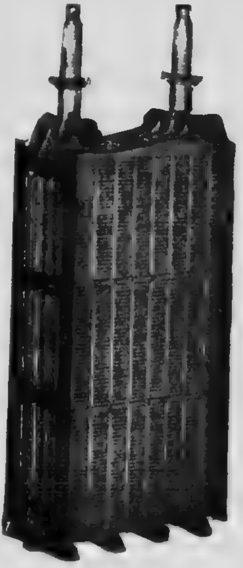

Fig. 1,091.—Edison C removed from the C taining Box.

The + and − sections are interleaved in the usual way with − plates on the outside as in a lead battery, and small ebonite pins are placed between the plates to keep them separate. The unit is completed by grooved side insulators being placed over the edges of the plates. The containing box into which it is now slipped is also made of nickel-plated sheet steel, corrugated for strength, bent into shape welded along one side by an oxy-acetylene flame. The bottom is welded on in the same way. The nuts referred to above, when the plates are placed in the box, rest upon insulators, and sheets of ebonite are inserted at the ends to insulate the outside − from the metal of the box. When the whole unit in place the top is welded on, hermetically sealing the cell except [illegible] combination valve and filler seen in Fig. 1,080. This top cannot [illegible] moved without destroying the box—very good evidence that th eriodical and minute inspections necessary in lead batteries are not quired here. The poles project through openings in the top, from hich they are insulated by indiarubber and ebonite washers and bushings hich effectually prevent the passage of gas or electrolyte.

The cells, when finished, are coated with an insulating and protective int and assembled in trays similarly treated. The cell connectors are pper rods nickel-plated and fitted with steel lugs with internal tapers fitting taper of the cell electrodes seen Fig. 1,091; they are made fast by dinary nuts.

It is interesting to note that all the eet steel used after being nickel lated electrolytically is annealed at a d heat in an atmosphere of hydrogen, ensure that the nickel coating hall not peel off.

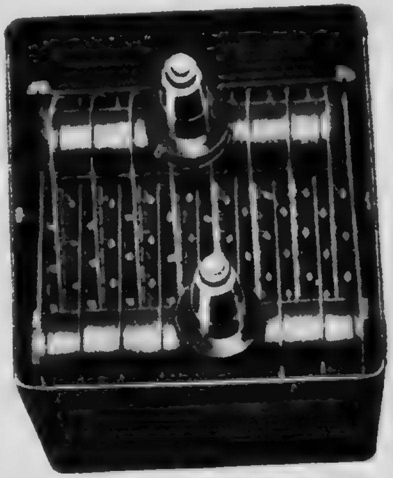

Fig. 1,092.—View of Edison Cell [illegible] with Cover removed.

Sizes of Cells. There are at esent ten standard sizes of cells, at only two standard sizes of plates. All plates are of the same thickness nd width, but what are known as the "B" plates are only one-half the ngth of the more generally used "A" lates. The cells are referred to by umbers, B-4, A-10, etc., the number specifying the number of "+" plates n the cell. As in the case of lead secondary cells the number of "−" is lways one more than the number of "+". The weights of the cells in ach type are almost proportional, but not quite, to the number of +, the weight of the A-4 cell being 13·3 lb. and that of the A-12 cell 41 lb. The over-all dimensions of the largest, the A-12, cell are 7·37 inches long 5·50 inches wide, and 14·62 inches high, the height of the containing case eing 12·75 inches.

Rating.—The cells are rated as having a capacity of 37·5 ampere-hours per + plate in the "A" sizes and 20 ampere-hours per + plate n the "B" sizes; but the normal actual output on a seven-hours' charge is 42 ampere-hours per + plate in the "A" sizes, and exactly one-half r 21 ampere-hours per + plate in the "B" sizes. The maximum output n overcharge is 47·5 ampere-hours per + plate for "A" and about one-alf of this for "B" sizes. The rate of discharge, as we shall see later does not have the great effect on the output capacity which it has in th lead secondary cell.

Theory of the Cell. The principal chemical actions which take place (i.) on first formation, (ii.) on discharge, and (iii.) on recharge have been carefully ascertained and are fairly simple.

The oxides originally used in constructing the cell are nickel hydrate [$Ni(OH)_2$] on the +ve plate and ferric oxide (Fe_2O_3) on the −ve plate. The electrolyte is potassium hydrate [$K(OH)$], in which the free ions at any time will be potassium (K), +ve charged and hydroxyl, (OH) −ve charged. On passing the first charging current from the nickel to the iron element of the cell, the former becomes +ve charged and attracts the −ve ions, and the latter becomes −ve charged and attracts the +ve ions. These ions may be regarded as combining with the oxides on the plates according to the following equations :—

Positive plate : $3\,Ni(OH)_2 + [6\,(OH)]^* = 3\,NiO_2 + 6\,H_2O$ . . (i.)
Negative plate : $Fe_2O_3 + [6\,K] = 2\,Fe + 6\,KOH$ . . (ii.)

The nett result is that the nickel hydrate is oxidised to a nickel peroxide, the ferric oxide is reduced to metallic iron, and the dissociated potassium hydrate is re-formed.

In the subsequent *discharge* this process is not exactly reversed, for the ordinary ferric oxide and nickel hydrate are never again re-formed ; but in their stead there appear magnetic oxide of iron (Fe_3O_4) and an exactly similar oxide of nickel (Ni_3O_4), according to the reactions shown in the following equations, in considering which it must be remembered that on reversing the current the iron and nickel plates become respectively +ve and −ve charged, and attract the oppositely charged ions of the electrolyte :—

Positive plate : $6\,NiO_2 + [8\,K] + 4\,H_2O = 2\,Ni_3O_4 + 8\,K(OH)$. (iii.)
Negative plate : $3\,Fe + [8(OH)] = Fe_3O_4 + 4\,H_2O$ . . . (iv.)

On *recharging*, the last operations are reversed, the Ni_3O_4 being oxidised to NiO_2 and the Fe_3O_4 reduced to metallic iron by the action of the − and +ve ions respectively, the equations being as follows :—

Positive plate : $2\,Ni_3O_4 + [8\,(OH)] = 6\,NiO_2 + 4\,H_2O$ . . (v.)
Negative plate : $Fe_3O_4 + [8\,K] + 4\,H_2O = 3\,Fe + 8\,K(OH)$. (vi.)

The above equations (iii.) to (vi.) give the final effects of the actions at the plates on discharge and charge. The actual actions taking place and leading to these results may be more complicated. The +ve charged ion K, on arriving at a −ve charged plate in equation (iii.) or (vi.), may be regarded as giving up its electric charge and then decomposing a molecule of water (H_2O), and forming K(OH) and H ; the former remains in the solution, whilst nascent hydrogen reduces the metallic oxide, in contact with which it is formed to Ni_3O_4 in one case, or to metallic iron in the other. Similarly the — charged ion (OH), arriving at a + charged plate in equations (iv.) or (v.), may be regarded as giving up its electric charge, and then acting on the neighbouring H_2O, liberates O, which oxidises the Fe or the Ni_3O_4, in contact with which it is formed to Fe_3O_4 in one case and to NiO_2 in the other.

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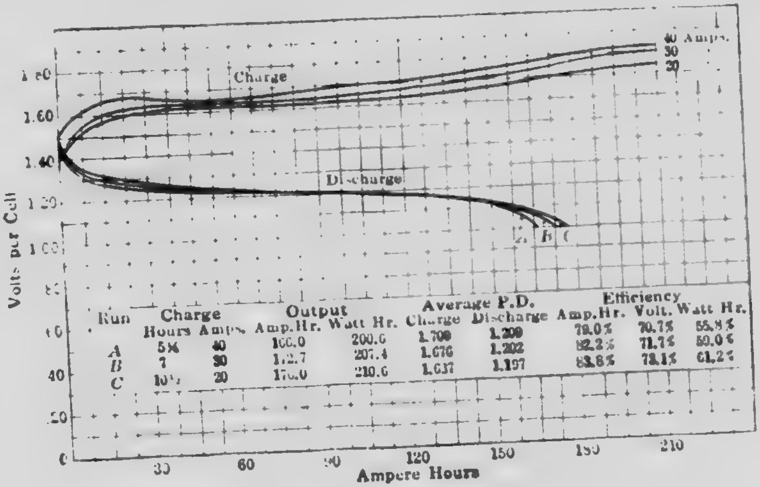
* See note on page 1051 regarding the meaning of the square brackets.

Whatever be regarded as the actual process the nett result is as given in equations (iii.) to (vi.), and, as stated elsewhere, whether in charging or discharging, the composition of the electrolyte on balance remains unchanged, a very different result from that obtaining in the lead secondary cell. Therefore only a small quantity of the electrolyte is required, and it is not necessary to take continual readings with a hydrometer to ascertain its state. In practice it is found that fully three hundred cycles of charge and discharge may be made without examining the electrolyte and then the simplest method is to renew it, which is neither a difficult nor an expensive process.



Run	Charge		Output		Average P.D.		Efficiency		
	Hours	Amps.	Amp.Hr.	Watt Hr.	Charge	Discharge	Amp.Hr.	Volt.	Watt Hr.
A	5¼	40	166.0	200.6	1.700	1.209	79.0%	70.7%	55.8%
B	7	30	172.7	207.4	1.676	1.202	82.2%	71.7%	59.0%
C	10½	20	176.0	210.6	1.637	1.197	83.8%	73.1%	61.2%

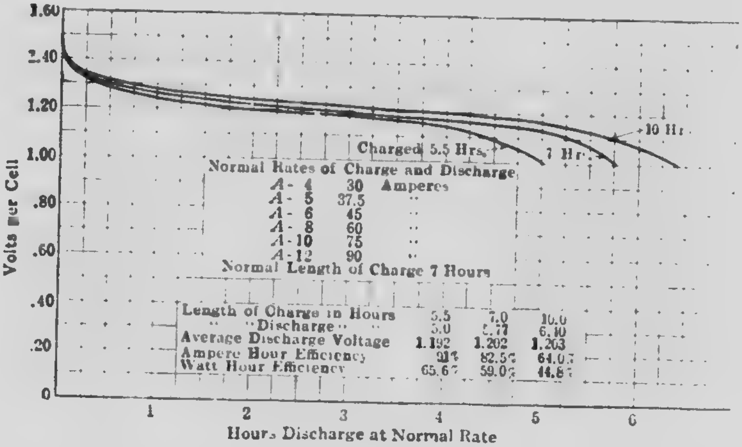
Fig. [illegible] — Charge and Discharge Curves of an Edison Secondary Cell.

Further, the active materials of the plates are insoluble in, and are not acted on in any way by, the electrolyte, and thus no chemical deterioration takes place. Certain physical changes which caused trouble in the early patterns of cells have been eliminated by careful attention to minute details of preparation and construction found to be desirable as a result of long-continued experiments and research.

Performance of the Cell. Very thorough tests have been made and published of the performances of these cells under fair regular and under unfair exceptional conditions. From these we select, for the limited space at our disposal, a few which appear to be of the greatest interest more especially by comparison with lead battery working.

In Fig. 1,093 typical charge and discharge curves of an A-4 cell are given for three different rates of charge, viz. 40, 30, and 20 amperes, the normal rate for this size being 30 amperes. The abscissæ are in ampere-hours, and the ordinates, the P.D., in volts. Each charge being at constant current, the ampere hours for that charge are proportional to the time, but the time-scale is different in each experiment. In each case the cell is charged with the same number of ampere-hours, namely 210, but the actual times of charging are 5·25, 7, and 10·5 hours respectively.

It will be noticed that although at the beginning of charging there



Normal Rates of Charge and Discharge

A- 4	30	Amperes
A- 5	37.5	"
A- 6	45	"
A- 8	60	"
A-10	75	"
A-12	90	"

Normal Length of Charge 7 Hours

Length of Charge in Hours	5.5	7.0	10.0
" " Discharge " "	5.0	5.77	6.10
Average Discharge Voltage	1.192	1.202	1.203
Ampere Hour Efficiency	91%	82.5%	64.0%
Watt Hour Efficiency	65.6%	59.0%	44.8%

Fig. 1,094.—Discharges after Different Periods of Charging at Normal Rate.

is, as in the lead cell (*see* Fig. 1,076, page 1048), a rapid rise of voltage, the remainder of the curve is very different. The discharge, which is taken at 30 amperes in each case, more nearly resembles that of a slowly discharged lead cell—for instance, the top curve in Fig. 1,074, page 1046. In each case the discharge is continued until the P.D. has fallen to 1·0 volt, and after the rapid charge this P.D. is reached a little over twenty minutes earlier. The full data of the experiments are given in the table on the diagram.

The effect of the time of charge on the discharge curves is shown in Fig. 1,094, in which the results are given of experiments at normal rates of charge and discharge, the time of the charge being varied from 5·5 to 10 hours. This increase of the time of charge gives only an increase in the time of discharge from 5·0 to 6·4 hours, with a corresponding diminution of the proportion of the ampere-hours given up on discharge. The ell is thus much more efficient on the shorter than on the longer charges nd discharges. The explanation given is that the ampere-hours lost are ed up in electrolysing water into hydrogen and oxygen, which escape s gases, and not in doing useful chemical work at the electrodes. To re- lace these los[illegible] pure water has to be added from time to time, though hen the battery is standing idle no water is lost by ordinary evaporation.

Constant-current discharges at rates varying from 15 to 180 amperes ive an almost constant total output if the discharge be carried practic- lly to zero P.D. in each case, the cell being given a seven hours' charge at normal rates after each discharge to zero. The effect on the total output in ampere-hours, therefore, of the rate of discharge, unlike the case of the lead cell, is very small. The effect on the voltage, however, is very marked. These effects are shown clearly in Fig. 1,095, in which the abscissæ denote

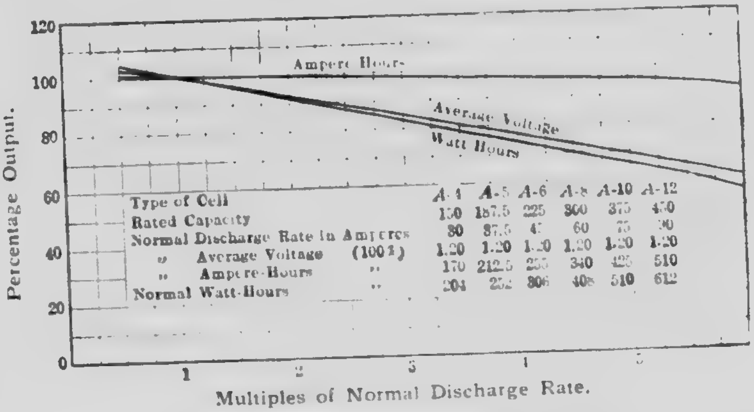


Fig. 1,095.—Output of Cells for Different Discharge Rates.

the rate of discharge in terms of the normal rate taken as unity, and the ordinates give the percentage of the normal for [illegible] the ampere-hours, (ii.) the P.D. in volts, and (iii.) the [illegible]tt-hours.

Resistance.—An important fac[illegible] the difference between the charging and discharging P.D. is, as e[illegible]d elsewhere [illegible] internal resistance of the cell. We cannot deal with this question at full length, but it may be stated that during discharge at normal rate the resistance remains very steady for the first four hours, and then rises rapidly until at the end of 5·25 hours it is about 2·4 times the earlier values. This earlier value varies from 0·003 ohm in the A-4 size to 0·001 ohm in the A-12 size.

Efficiency.—In some of the above diagrams there are given the watt-hour efficiencies which, as explained elsewhere, are the real or energy efficiencies, and it will be noticed that in most cases these are low, the maximum being 65·6 per cent. and the lowest 44·8 per cent. The condition which appears to have most effect on the efficiency in any given experiment is the length of the preceding charge. This is strikingly shown in Fig. 1,096, in which the percentage efficiencies and the percentage of the

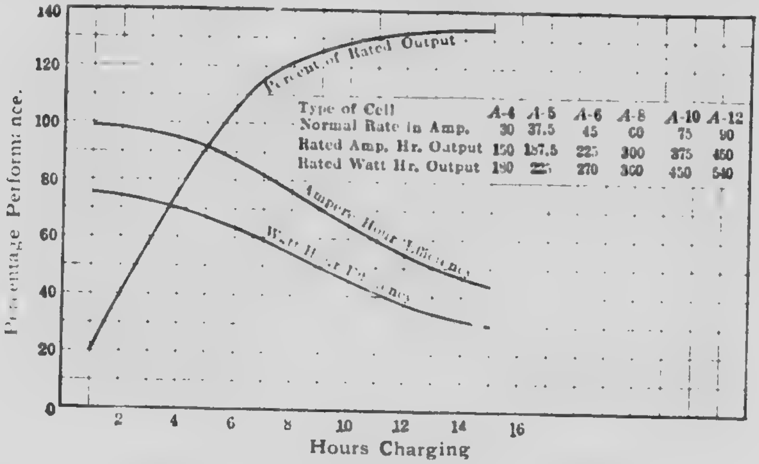


Fig. 1. . . Influence of Rate of Charge on Output and Efficiency.

rated output obtained are plotted against the "hours of charge." The charges in each case are at the normal rate, and only the period of charge is varied. For a one-hour charge the ampere-hour efficiency reaches 100 per cent. and the energy efficiency 75 per cent. The output is, however,

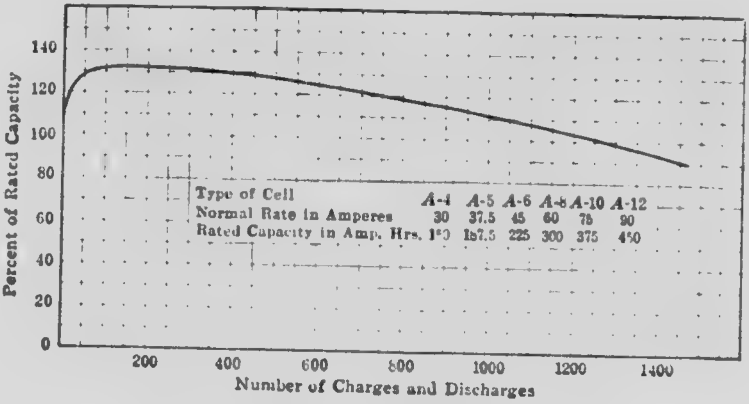


Fig. [illegible].—Life Curve of Capacity under Severe Conditions.

only 20 per cent. of the rated output. For a fifteen-hour charge, on the other hand, the ampere-hour efficiency has fallen to 55 per cent., and the energy efficiency has gone down to 30 per cent.; simultaneously, however, he output has risen to 133 per cent. of the rated output. The normal energy efficiency may be taken to be 60 per cent. and the normal ampere-hour efficiency 80 per cent.

Another interesting point in the working of these cells is the effect on the working capacity of successive charges and discharges as shown in Fig. 1,097. During the first 100 charges and discharges the capacity continuously rises, and does not appreciably fall until after 300 such cycles. After nearly 1,500 cycles the capacity is still 90 per cent. of the rated capacity.

Space does not allow us to give any more of these interesting curves; but enough have been given to show how greatly the performance of the Edison cell differs from that of the lead cell. The great advantages of the cell are the very little attention it requires and its small weight, and the great disadvantage, from the point of view of its utilisation, is its low voltage, thus necessitating a greater number of cells to obtain a given voltage.

Notwithstanding these drawbacks, and chiefly in view of its small weight and the slight amount of technical attention required, it has of late years made very substantial progress in road traction work. Its utilisation for this purpose is described in the chapters on "Electric Traction" (*see* pages 1381 *et seq.*).

CHAPTER X

RECTIFIERS

In addition to the kinetic transformers described in Chapter VIII., there are various other methods of transforming alternating into continuous currents. The principles of the more important of such methods have been dealt with historically in Vol. I. (*see* page 565 *et seq.*). The apparatus is usually described as a "rectifier." Of the methods referred to only three have any fairly extended application at the present time in electrotechnics, namely –

(i.) Mercury-arc rectifiers,
(ii.) Hot-kathode rectifiers,
(iii.) Electrolytic rectifiers,

which will now be considered and described in the order named.

I.—MERCURY-ARC RECTIFIERS

The principle upon which such rectifiers are based has been explained in Vol. I. (*see* page 569), and an early form has there been illustrated and described. The form referred to was devised for three-phase circuits upon which it is easier to use such rectifiers than on single-phase circuits.

It has been pointed out (*loc. cit.*) that this rectifier is a mercury-vapour lamp (*see* Vol. I., page 673 *et seq.*) with one or more *solid* electrodes which act as lamp anodes and can never act as kathodes, and a *liquid* mercury electrode which, under the circumstances, is never called upon to act as an anode, and therefore always acts as a kathode. In other words, current can only pass through the rectifier from a solid electrode to the mercury electrode, and never in the opposite direction. Hence the apparatus if supplied with an alternating current can only pass through it the half of the current wave which is in one direction, and suppresses the half which is in the other direction. The leads connected to the lamp therefore carry unidirectional currents.

The first difficulty when working with *single-phase currents* is to secure that the mercury kathode shall receive current during the period that intervenes between the end of one "+" loop of current on a particular solid anode and the beginning of the next "+" loop, that is, during the "—" half-period. This is accomplished by constructing the lamp with one mercury cup kathode, K (Figs. 1,098, 1,099), and two anodes A and A′, the latter being connected to the opposite sides of a single-phase supply circuit so that one is always —' when the other is +', and vice versa.

The present standard apparatus is an application of the principle of the auto-transformer; the connections are shown in Fig. 1,098. The terminals T_1 T_2 of the supply circuit are connected to the windings of the transformer at some distance from the terminals k_1 and k_2, and a tapping is provided at the middle point *a* of the winding. The converter proper—that is, the mercury-vapour lamp—is, as already mentioned, constructed with two anodes A_1 and A_2 and one kathode K, and is often, though not necessarily, of the shape shown. The anodes A_1 and A_2 are usually made of graphite, the kathode metal being liquid mercury contained in the small tube at K. A rectifier of this pattern, shown in Fig. 1,099, is manufactured by the Westinghouse Cooper-Hewitt Company, of London. The anodes are connected respectively to the terminals k_1 k_2 of the transformer; the kathode K and the central point *a* of the winding are respectively connected to the +' and —' terminals C_1 C_2 of the continuous-current secondary circuit, of which C_1 is the + pole and C_2 the —'. In one of these connections there is interposed a reactance R. When T_1 is +' and T_2 —', besides the current direct from t_1 to t_2, a parallel current flows through the loop t_1, k_1, A_1, lamp, K_1, C_1, load, C_2, R, *a* to t_2, the loop A_2 k_2 t_2 being out of action. Half a period later, the conditions are reversed, the right-hand loop being in action and the left-hand loop out of action.

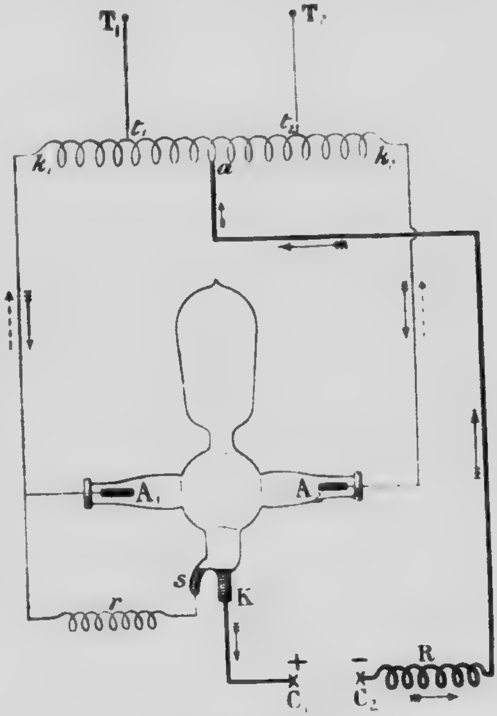


Fig. 1,098. Connections for a Single-phase Mercury-arc Rectifier.

The current cannot, however, be allowed to die down to zero in either loop, as there is a back E.M.F. of about 15 volts in the lamp (apart from its resistance). The reactance R is therefore inserted in the C.C. part of the connections with the purpose of producing an inductive E.M.F. when the current is diminishing which will be sufficient to maintain the voltage in the lamp until the voltage of the mercury loop has risen sufficiently to take up the running. A further consequence of the insertion of R is that the rising current is cut down by a back E.M.F. in R, and thus instead of a rectified current from C_1 to C_2 fluctuating between zero and a maximum, there is a pulsating current which never sinks to zero but, on the other hand, does not reach so high a maximum. This is to the good.

It is further necessary to provide for the starting of the action, and it is for this purpose that the second small mercury electrode S is provided. The main terminals T_1 and T_2 being alive but no current passing through the rectifier, the latter is tilted until the mercury in S and K form a continuous conductor along which the current can pass in either direction. On breaking this bridge the arc forms and at once ionises a sufficient number of molecules of the residual gas in the bulb, thus providing the necessary path for the mercury arc to pass from A_1 and A_2 to K. The subsidiary reactance *r*, in series with S, obviously assists this action and also acts as a buffer, preventing S acting permanently as an electrode when the rectifier is working.

F[illegible] Rectifier for [illegible] Volts.

Theory of the Mercury-arc Rectifier. In the diagram in Fig. 1,098 an auto-transformer is shown and there is obviously a definite relation between the R.M.S. voltage of the supply mains and the average or the R.M.S. value of the pulsating unidirectional current at the terminals C_1 C_2. It is further obvious that if there is a great difference between these two voltages it can be adjusted, and any required voltage obtained at C_1 C_2, by using a suitable static transformer whose primary is placed across the supply mains and whose secondary coil will take the place of the coil k_1, k_2 in Fig. 1,098, the other connections being unchanged.

There is always a drop of voltage in the vacuum tube, consisting partly of a back E.M.F. at the electrodes and also of a drop in the mercury vapour column; both of these are independent of the current, and their joint effect is a loss of about 15 volts. The energy absorbed by the bulb will be this voltage multiplied by the mean value of the current, and therefore will be directly proportional to the current. The energy so absorbed, by whatever process, is eventually turned into heat, and has to be dissipated. As the current increases the radiating surface of the bulb must be increased so as to dissipate this energy, and it has been found that there is a limit beyond which glass becomes an unsuitable material. The highest current for which glass bulbs have been regularly utilised appears to be 80 amperes. If heavier currents are required in the C.C. circuit several glass bulbs can be put in parallel, but practical limitations are again soon met with.

[illegible]

Where heavy currents are to be handled metallic converters are used, but the change of material introduces new difficulties. For the proper working of the [illegible] a high vacuum [illegible] has to be [illegible] and maintained. This raises difficulties in making [illegible] and insulated joints through which the conductors can be connected to the external circuits. The [illegible] adopted are described later. Incidentally, the [illegible] metal allows the apparatus to be water-cooled, and with [illegible] assistance in dissipating the energy [illegible] the size of the apparatus can be reduced.

As regards the voltages which may be employed, one of the difficulties is the danger of an arc forming between the anodes, between which, it must be remembered, there is always an A.C. potential difference. If such an arc forms it is practically a short-circuit, and a large surge of current will pass. In the case of a glass bulb this destroys the bulb, but with a metallic converter it simply blows the fuse or operates any protective overload device which may be in use. If such an arc does not form, the reverse current between the solid anodes is very small, being only about 0·0 milliampere at 110 volts with 60 amperes passing in the other direction. The glass bulb shown in Fig. 1,099 will safely deal with 110 to 150 volts. For higher voltages a longer and more difficult path is provided between the anodes, such as is shown in Fig. 1,100, which shows a bulb for 500 to 600 volts with a three-phase supply. Short circuits are more frequent with three-phase than with single-phase bulbs, because of the superposing of the currents and the greater quantity of ions developed.

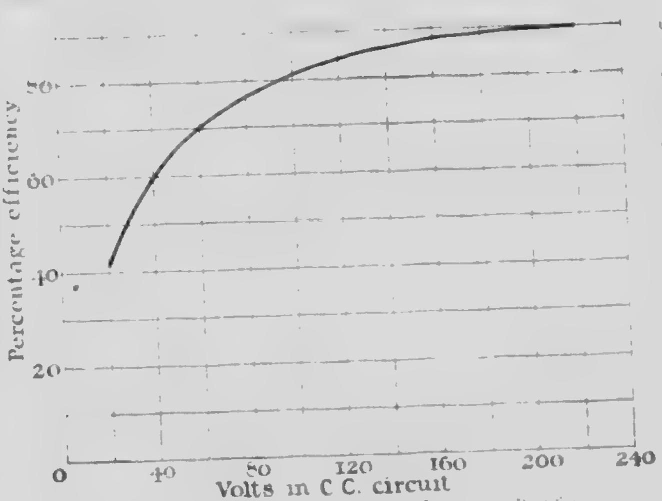


Fig. 1,101.—Efficiency of the Bulb of a Mercury-vapour Rectifier.

Efficiency.—The principal transformation loss is due to the voltage drop in the bulb, which, as we have explained, is of the order of 15 volts.

The efficiency will therefore depend upon the voltage required in th load circuit, and will increase as this voltage rises. A curve showing th efficiency for different voltages is given in Fig. 1.101, from which it wi be seen that the efficiency rises from a little over 40 per cent. at 20 volt to 90 per cent. at 220 volts, no account, however, being taken of th losses in the static transformer but only in the rectifier. In measurin the current and voltage in the C.C. circuit the fact that the current an voltage are pulsating, and not either truly alternating or of steady continuous values, must be borne in mind, and the instruments calibrate accordingly. Efficiency curves for much smaller voltages and loads ar given in Fig. 1.102, in which the curves A and B show the efficiencies fo small portable rectifiers, made by the General Electric Company o Schenectady, for charging a three-cell (curve A) and a six-cell (curve B) secondary batter for petrol motor ignition circuits The efficiencies are plotted against the load in the C.C. circuit, which has a maximum value of les than 60 watts for curve A and 82 watts for curve B.

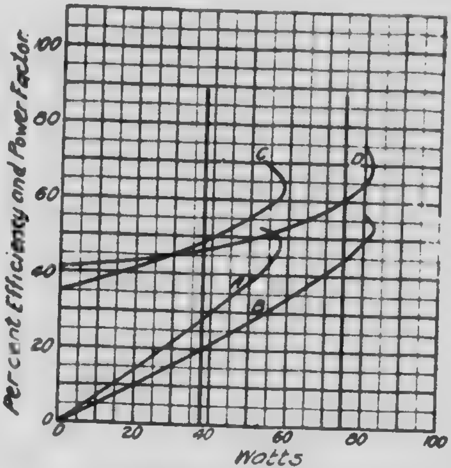


Fig. 1.102.—Efficiencies and Power Factors of Small Mercury-arc Rectifier.

For very high voltages the 15 volts lost in the bulb becom negligible, and at such voltages the rectifier becomes a source of high-voltage continuous currents of great efficiency, the chief loss being in the static transformer. As indicating what has been done in this direction, it may be mentioned that the Marconi Wireless Telegraph Company have a mercury vapour outfit designed for an output of 10 amperes at 13,000 volts. At this voltage the bulb loss is only a little over 0·1 per cent.

Power Factor.—The power factor of the primary circuit is about 0·9 when no special inductance has to be introduced, such as is desirable when supplying current to single arc lamps for projection work. Power factors for small outputs are much lower. Two curves C and D given in Fig. 1.102 are for the small cell-charging rectifier referred to above. The highest value of the power factor in these curves is about 0·75, and for some of the working [illegible] of the load falls below 0·50.

Practical Applications.—The advantages of a mercury-arc rectifier are that it practically requires little or no attention when once started, has no moving parts, contains no chemical liquids, and evolves no corrosive vapours. In all cases where continuous or unidirectional currents are necessary and only alternating currents are supplied, there would seem to be a field for its practical use, and, provided the cost is not too great, it should only require that the necessary apparatus should be so assembled and arranged that it can be readily manipulated in accordance with simple instructions to ensure its use in ordinary daily work. For heavy engineering operations, where skilled technical supervision is available, other considerations determine its adoption or rejection.

Low-power Applications. It has been stated above that glass-bulb rectifiers can be trusted to carry currents of 30 amperes, and that such rectifiers are certainly more convenient for ordinary use than the heavy current metallic rectifiers which have been more recently developed. For purposes which require currents below 30 amperes quite convenient arrangements can be made, and the apparatus is well adapted for the following practical applications:

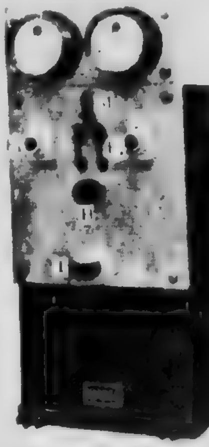


Fig. 1.103. – Simple Panel for Mercury-arc Rectifier.

(i.) The charging of secondary batteries for electromobiles of both high and low voltage, for automobile engine ignition and head-lights, and for telephone and telegraph purposes.

(ii.) The operation of kinematograph and other projection arcs, which are seldom satisfactory with alternating currents.

(iii.) The operation of various kinds of electro-medical apparatus, such as X-ray apparatus, thermo-cautery apparatus, small motors for dentists, etc. etc.

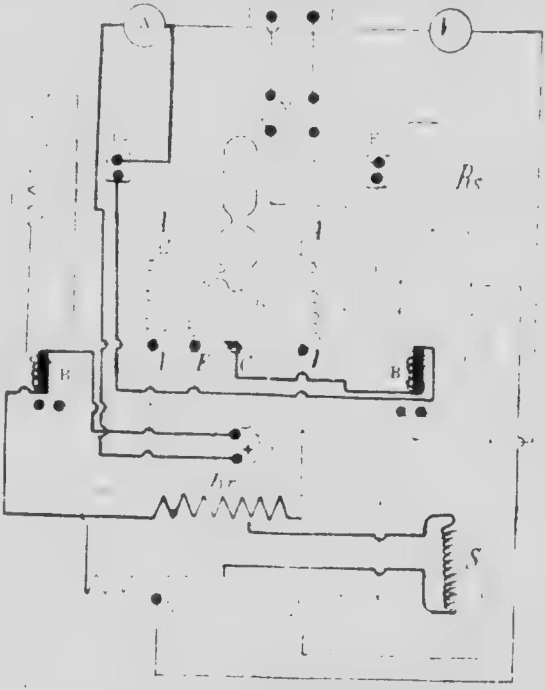
(iv.) The operation of electro-magnetic control apparatus.

(v.) General laboratory work, where the alternating current available is useless, or does not give as good results as unidirectional currents.

For purposes such as those enumerated special outfits are available, the chief designers and manufacturers hitherto being the Westinghouse Cooper-Hewitt Company, Ltd., London, and the General Electric Company of Schenectady, New York.

The standard panel for a five- or ten-ampere bulb, as manufactured by the Westinghouse Cooper-Hewitt Company, is shown in Fig. 1.103. The mercury rectifier is mounted behind the panel, and for starting purposes can be rocked by the handle H. The + and — terminals for the C.C. current are in the plug socket T at the bottom of the panel; in addition, there is a D.P. main switch M for the main A.C. circuit and two sizes [illegible] 5 and 10 amperes respectively. [illegible] transformer [illegible] the lower part [illegible].

The [illegible] shown in Fig. 1,104, in which the same [illegible] letters are used as in Fig. 1,103 [illegible] starting [illegible] Fig. 1,103, and [illegible] for all [illegible] [illegible] An inductive coil is inserted in the load circuit, in which are [illegible] the two magnet [illegible] and the other a shunt on the main circuit. The ammeter [illegible] is in the C.C. circuit, and the voltmeter V is bridged across the terminals [illegible] the load circuit.



[illegible] Mercury [illegible] Rectifier.

The 5-ampere size will [illegible] currents from 3 to 5 amperes, and the 10-ampere size currents from 4 to 10 amperes; it should be noted that there is a minimum as well as a maximum current, hence the provision of the shunt R (Fig. 1,104) to keep the tube going when the current in the load circuit is too small. The use of such a shunt of course reduces the efficiency of the transformation. The A.C. voltage may be from 100 to 240 volts at 40 to 60 ∾, the apparatus being adjusted for the particular supply voltage available.

The standard panel for large currents is as shown in Figs. 1,105 and 1,106, of which Fig. 1,105 is a front view and Fig. 1,106 a back view, with the protecting casing removed. The multiple switch at the bottom of the panel regulates by varying the number of turns in the primary of the transformer. Circuit breakers take the place of the fuses in Figs. 1,103 and 1,104, and a single pole switch is inserted in the starting circuit. The standard sizes for the rectifier bulbs give maximum currents of 30, 40, 60, and 80 amperes, the minimum currents being 8, 10, 20, and 30 amperes respectively, and the supply voltages from 100 to 240 volts at 40 to 60 ∾. The maximum voltages in the C.C. circuit vary from 40

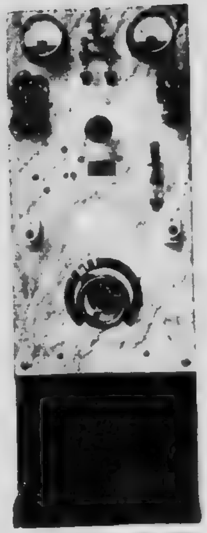


Fig. 1,105. — Standard Panel for Currents [illegible] Amperes.

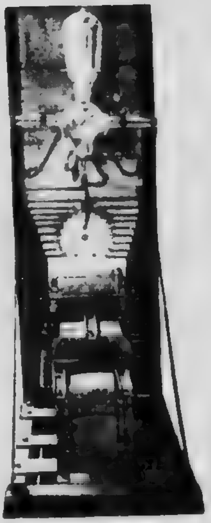


Fig. 1,106. — Rear View of 80-ampere Panel.

to 250 volts. The panel is 20 inches wide and 50 inches high and at maximum load has a c.c. output of 20 kw.

One of the standard panels of the General Electric Company is shown in Figs. 1,107 and 1,108, the former being a front view and the latter a rear view of the panel. The panel is designed to be used directly on a consumer's 110- or 200-volt single phase circuit, and there is therefore no step-down transformer. The main auto-transformer or compensator, as it is called, is contained in the iron case standing on the floor, and is connected to the tap studs on the right-hand side of the double-regulating dial switch on the lower part of the panel. This side of the switch gives the coarse adjustment for varying the voltage supplied to the vacuum tube over a wide range, according to the C.C. voltage required. The left-hand side of the switch has eleven contact points connected to the small "compensator" seen in Fig. 1,108, behind the panel, and the movements of this switch give a fine adjustment of the voltage. The regulation so obtained is such that on a 220-volt circuit C.C. voltages from 20 to 175 volts can be obtained in a great number of graded steps, and there are corresponding adjustments for a 110-volt circuit. The maximum current obtainable is, as usual, determined by the size of lamp used, there being five standard sizes of 10, 20, 30, 40, and 50 amperes capacity respectively. The tubes are shown in Figs. 1,109 and 1,110 the former being for the 110-volt and the latter

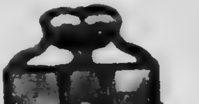


Fig. 1,107.

Fig. 1,108.

G. E. Standard Battery Charging Rectifier Set.

for 220-volt supply circuits. The reasons for the differences have been already explained elsewhere.

The other apparatus on the panel is simple, and will be best referred to by a description of the process of starting up, which applies to the other panels illustrated. The double dial switch having been set to the proper position for the C.C. voltage required, the double-pole main switch on the left and the circuit breaker at the top of the panel are both closed. The spring switch on the extreme right is then moved to, and held in, the starting position, whilst the tube behind is rocked by means of the handle close to the starting switch. As soon as the tube lights up, showing that the mercury arc is formed, the starting switch is released and automatically springs back to the working position.

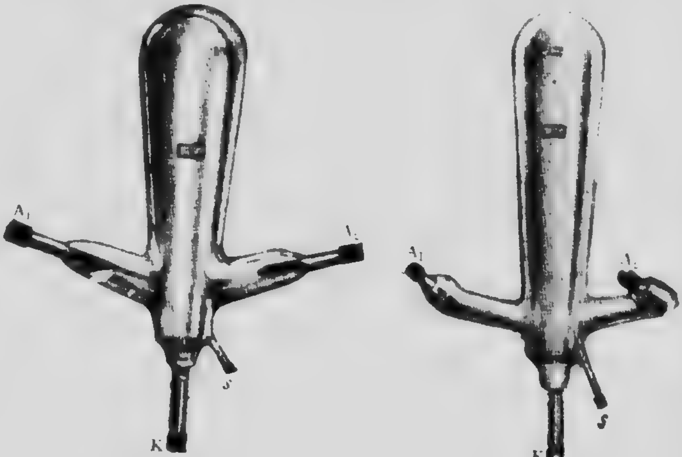


Fig. 1,106. Fig. 1,107.

G. E. Standard Rectifier Tubes to 50 Amperes at 220 Volts.

The action of the starting switch just referred to has yet to be explained. Owing to the fact that the poles of the battery to be charged are connected to the terminals r (*see* Fig. 1.104), the kathode K is polarised as an anode, and the anodes A_1 A_2 are polarised as kathodes by the battery before the current is switched on. Against this counter E.M.F. the rectifier will not start readily, and therefore a non-inductive resistance is mounted as an auxiliary starting load on the back of the panel, and when the starting switch is pulled over the battery is cut-out and this resistance placed across the mains. When the switch flies back to the working position the battery is restored and the starting load cut out. The instruments mounted on the top of the panel are an ammeter and a voltmeter placed in the C.C. circuit for measuring the C.C. output.

Similar panels have been standardised for kinematograph operating, for charging small batteries, and for working small motors. As already mentioned, there are ten standard sets of tubes.

Battery Charging.—An installation of the Westinghouse Cooper-Hewitt pparatus, specially erected for the charging of automobile secondary atteries, is shown in Fig. 1,111. It consists of a control panel at the end f the room facing the spectator and of rectifier panels on either side. here are nine rectifier panels shown in the figure with space for a tenth.

On the control panel there is a D.P. main switch M with an ammeter A_1 and a D.P. fuse F, all in the main supply circuit. The supply voltage is 220 volts single-phase at 50 ∞, and is switched direct on to the rectifier panels. In the panels circuit there is an ammeter A_2 and a voltmeter V, with a D.P. switch S supplying current to busbar leads which run round behind the rectifier panels on either side. An integrating wattmeter was later placed in the rectifier circuit at W. The other switches control lighting and power circuits not connected with the rectifiers.

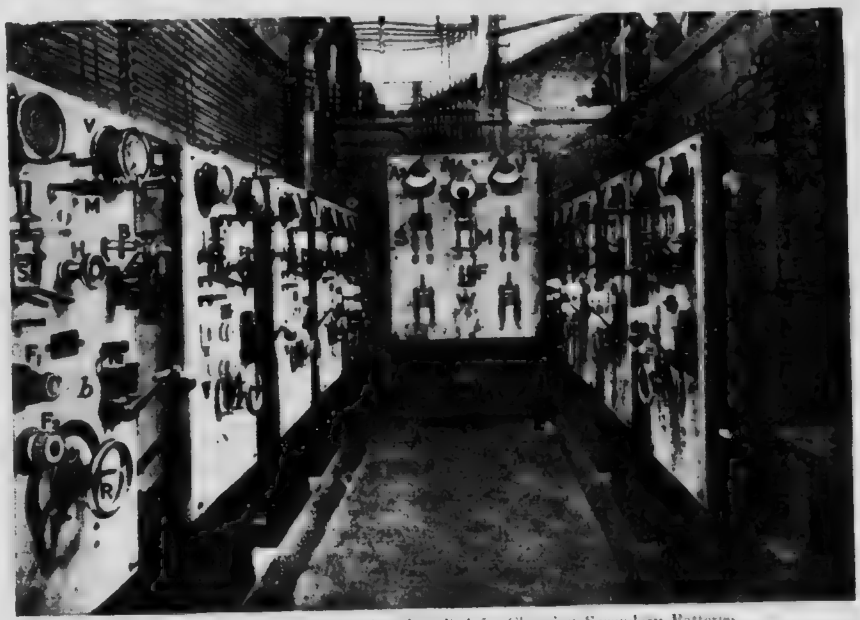


Fig. 1,111.—Mercury-arc Rectifiers Installed for Charging Secondary Batteries.

The rectifiers used are of the 30-ampere size, and the maximum output of each panel is 30-amperes at 120 volts, sufficient for an ordinary automobile battery. On each panel there is a D.P. main switch M in the A.C. circuit,* a starting switch S for the branch starting circuit (*see* Fig. 1,104), and a tilting handle H for tilting the rectifier on starting; also S.P. fuses F_1 and F_2 in the A.C. and C.C. circuits respectively, and a voltage regulator R, connected to different tappings on the auto-transformer. The instruments are an ammeter A and a voltmeter V in the C.C. circuit, and two circuit

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* Only the panel on the extreme left is lettered.

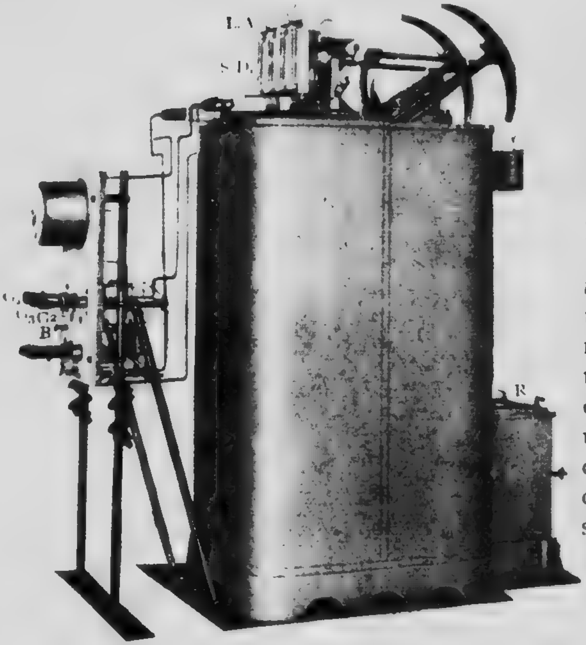


Fig. 1,112.—Series Mercury-arc Rectifier with Switch Panel.

breakers B and *b*, B set to open on overloads, and *b* set to open when the current falls below a certain minimum. The installation is compact and well adapted for the purpose in view.

High-power Applications.—In actual practice the applications of the mercury-arc rectifier to the handling of large quantities of power have, up to the present, been chiefly, though not exclusively, devoted to two special operations. In one of these the load consists of a large number of magnetite or luminous arc lamps in series requiring a small current at a high voltage, for which purpose one small-current glass-tube rectifier or two such tubes connected in series are used. In the other a high-power continuous-current locomotive picks up single-phase current from a high-voltage overhead line, and the requisite continuous currents are supplied to its motors from a single metallic-cased rectifier.

For the first-named purpose, in which small-current glass-contained rectifiers are used, the combined set as designed and manufactured by the General Electric Company of Schenectady is shown in Fig. 1,112, which is an external view of a single-tube apparatus, including the operating switch panel. The mercury tubes used in these sets are illustrated in Fig. 1,113, which differs chiefly from the tubes previously illustrated (i.) in the long length of narrow vacuum tubes

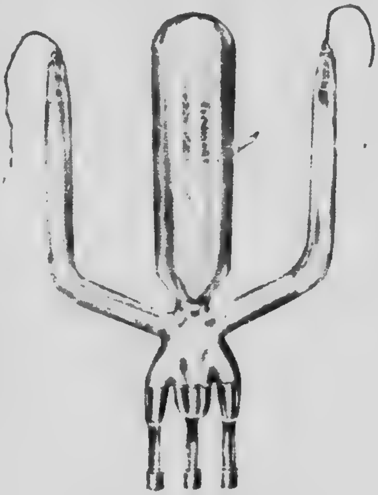


Fig. 1,113.—G. E. Rectifier Tube.

hich separate the two anodes from one another, and (ii.) in having two tarting electrodes, one on either side of the main mercury kathode, so at the action can be started by rocking the tube in either or both irections.

The apparatus, with the case removed, is shown in Fig. 1,114, and a iagram of the connections for a double-tube outfit is given in Fig. 1,115 rom which the single tube connections can be inferred by eliminating ne tube and the coils, etc., specially elonging to it. In either case only ne main transformer T is used. This transformer is of the constant-urrent type, and its primary P P is connected directly across the supply mains through the plug switches K K and the fuses *f f*, which are mounted on the lower part of the panel in Fig. 1,112. The primary coil of the transformer is mounted on rocker arms A A (Fig. 1,114), with a counter-balance weight W. It slides on the core of the transformer, and the current adjustment is made by altering the counter-balance weight. Should the current rise or fall whilst working, the movement of the coil will bring back the working voltage to the prearranged value by the necessary alteration of the voltage in the secondary coils S S. A reactance R (Fig. 1,115), mounted on the base and placed in series with the load, reduces the pulsations of the current in the load circuit.

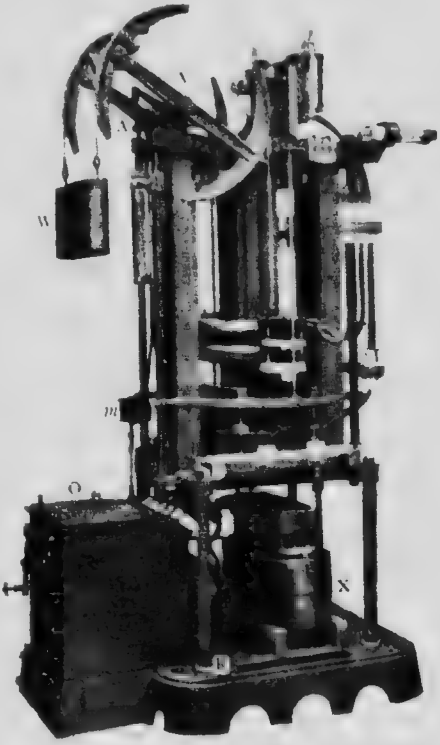


Fig. 1,114.—Single-tube Mercury-arc Rectifier Outfit

The standard voltage on the primary coil is 2,200 volts at 25 or 60 periods, and the only adjustment required is that some extra windings, known as the 80 per cent. tap, *t* in Fig. 1,115, are provided, which can be thrown into circuit on light load, thus reducing the voltage in the secondary circuit. The standard currents in the secondary for which the transformer is wound are 4, 5, or 6·6 amperes, according to the type of series arc lamp of which the load consists, and the standard current is from one-third to full load, independent of the number of lamps in circuit up to the maximum of twenty-five, fifty, or seventy-five lamps for which the particular set is designed. With the 80 per cent. "tap" the regulation is carried down to one-fifth of full load. The efficiency is 90 per cent., with a power factor of 0·65 to 0·70 at full load. Sets have been designed for frequencies up to 133 periods and for primary voltages up to 13,200 volts, but these are not standard. For loads of fifty or seventy-five lamps the double tubes of the diagram (Fig. 1,115) are used; the 25-lamp set has only one tube as shown in Fig. 1,112.

The part of the set shown without the case in Fig. 1,114, upon which is mounted most of the apparatus, is air-cooled; but the rectifier tube is oil-cooled, being immersed in oil in the small tank O. The oil itself is water-cooled by the circulation of water through a cooling coil immersed in it. The rectifier tube is mounted upon a removable carrier, as shown in Fig. 1,116, in which one carrier with its tube is seen in front of the tank, and another carrier is seen partly raised out of the tank. The arrangements for starting the action are first a solenoid electromagnet *m* (Figs. 1,114 and 1,115), mounted above the tube tank, which is bridged across the primary of the exciter transformer (see *infra*), and is thrown into circuit momentarily by the pull-button switch B (Figs. 1,112 and 1,115). On releasing the button the circuit is opened. When energised, *m*, by means of the tracker and spring attached to its solenoid, slightly rocks the rectifier tube so as to form the arc between the kathode and one of the neighbouring electrodes. To supply current for this arc when the tube is rocked, an additional secondary coil *s s* (Fig. 1,115) is wound on the constant-current transformer at the top of the core. This coil supplies current to the primary of a small exciter transformer X (Figs. 1,114 and 1,115), placed

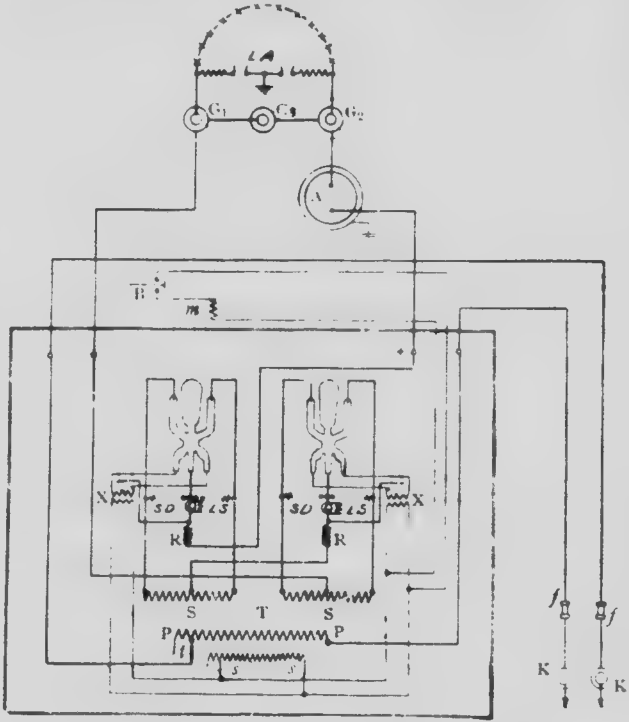


Fig. 1,115.—Connections of Double-tube Mercury-arc Rectifier Set.

n the base behind the oil tank; its secondary, which has quite a low voltage, has its middle point connected to the kathode of the tube and ts end terminals, one to each of the auxiliary electrodes. It thus can supply the necessary current whichever electrode comes into action.

As regards other apparatus, the ammeter A (Fig. 1,115) is on the panel and in the load circuit, which is at a high voltage, and therefore the outer case of the instrument is carefully earthed. Of the three upper plugs on the panel (Fig. 1,112), two, G_1 and G_2, act as a double-pole switch in the main circuit, and G_3 is a short-circuiting plug switch used to cut out the load instead of opening G_1 or G_2. Lightning arresters L A of the horn type, with series resistances, or aluminium cell lightning arresters, are mounted on each pole of the load circuit. In addition, static dischargers S D, consisting also of horn gaps with series resistance, are bridged across between each anode and the kathode. They protect the tubes from severe electrical strains. Indicating lamps L are placed electrically, as shown in Fig. 1,115, but actually on the top of the transformer to show whether the apparatus is working normally or otherwise.

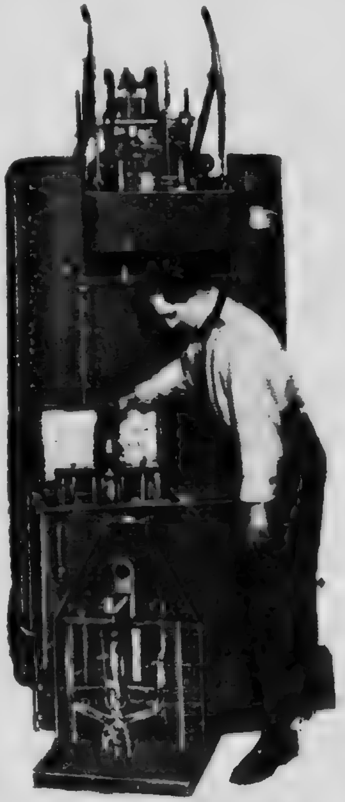


Fig. 1,116. Rectifier Set, showing Removable Carrier.

In conclusion, Fig. 1,117 shows thirty-six of these rectifiers in actual use in one of the main stations of the Union Gas and Electric Company in Cincinnati. Each set is a double-tube 75-lamp 4-ampere rectifier set, and, although in a generating station, the group is in effect a transforming sub-station capable of supplying current to 2,700 luminous arc lamps. Some idea of the size of the sets may be gained from the statement that they vary from 78 to 130 inches in height, from 31½ to 44 inches in width, and from 46 to 77 inches in depth without allowing for the space occupied by the switch panel. The net weight varies from 1,950 to 10,600 lb.

Life.—The question of the working life of rectifier tubes under the conditions just described is both interesting and important. A record kept of the rectifiers used by the Public Lighting Commission at Detroit gives an average life of over 2,900 hours, whilst two individual tubes lasted for 10,047 and 12,434 hours respectively. These results were obtained by skilled and careful handling, the temperature of the oil bath being kept constantly at 80° F., with observations every fifteen minutes. The rocking arrangement was also brought automatically into play to restart a tube if the current through it ceased.

The above figure for the average life applies to the tubes under working conditions, but with exceptionally skilled technical attention. Under ordinary working conditions, without such attention, but with reasonable care, the English manufacturers guarantee a life of 1,500 hours continuous burning, and will replace tubes which break down with a short [illegible] For intermittent working the guaranteed life is not so long.

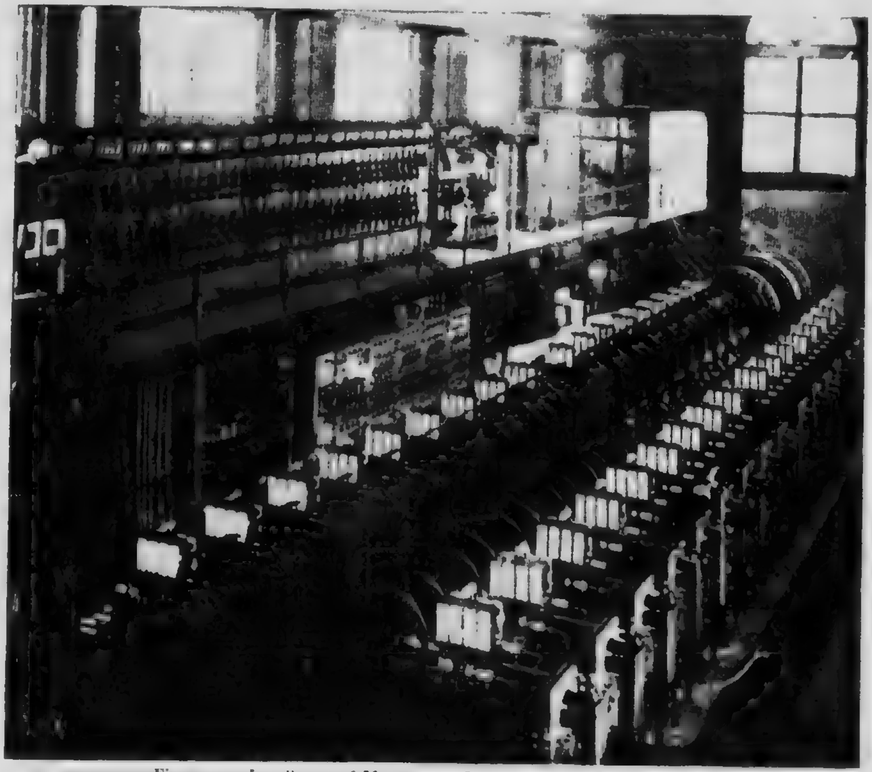


Fig. 1,117.—Installation of Mercury-arc Rectifiers in Generating Station.

Mercury-arc Rectifiers in Metallic Vessels.—The reasons for the limitation of the current in a mercury-arc rectifier enclosed in a glass vessel to about 80 amperes per bulb have been already explained (*see* page 1079). To handle larger currents metallic containing vessels are obviously desirable, and during the last few years much experimental work has been done in America and in Europe to overcome practical difficulties, the most troublesome of which have been (i) making the containing vessel sufficiently air-tight, especially at the places where the electric currents are led in and out; and (ii) providing efficient cooling arrangements and condensing chambers for the vaporised mercury.

Modern "ironclad" rectifiers are now made in which the arc is enclosed in a steel cylinder in a water-jacketed main chamber with separate condensing chambers also water-jacketed. As many as 12 anodes with capacities of from 50 to 200 amperes each have been used, these being mounted concentrically with one large circular cathode at the bottom of the main chamber. Such rectifiers have been standardised for currents of 250 and 500 amperes at 110 to 800 volts, the same rectifier being available for any voltage within the specified limits. Elaborate schemes for paralleling these rectifiers on one, two and three-phase networks have been successfully developed so that large amounts of power can be handled with them for the production of high-voltage continuous currents for traction or other work.

II. HOT-KATHODE RECTIFIERS

A vacuum tube, in which one of the electrodes is hot and the other cold, acts as a rectifier, the hot electrode behaving as a kathode and the cold electrode as an anode. The action is due to the emission of negatively charged electrons from the hot electrode. This emission, if the resultant "-ve" charges on the hot electrode are conveyed through an external circuit to the other electrode, will maintain in that circuit a unidirectional electric current which, if under proper control, can be utilised. It is with recent developments in connection with such control that we are concerned here, the theoretical aspects of the electric discharge, of which this is a special instance, being dealt with in Chapter XVIII. of Vol. I.

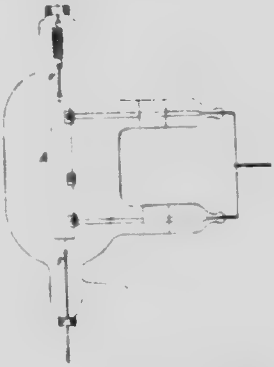


Fig. 1,118.—Simple Form of "Kenotron"

The Kenotron.—The Edison effect described in Vol. I. (*see* page 238) is an early instance of the phenomenon, but did not lead to any technical development at the time. Much more recently the subject has been taken up by Dr. Coolidge, who in 1913 described his now well-known hot-kathode X-ray tube in which voltages up to 100,000 volts are used. Still later in 1915 experiments by Dr. S. Dieshman, in the research laboratory of the General Electric Company at Schenectady, led to the development of the "*kenotron*," of which one simple type is shown in Fig. 1,118. A tungsten wire filament which can be raised to a high temperature by the passage of a current is mounted between the leads F F, and passes along the axis of a molybdenum cap or cylinder A.

[illegible] inch in diameter, which forms the anode. The supports of the cylinder act as leads for bringing currents to the anode.

If now the glass bulb be highly exhausted and an alternating P.D. be maintained between the cylinder A and the hot tungsten wire inside, only the half-wave of current which would be directed from the cylinder to the wire will pass, the other half-wave being suppressed. This result is shown in Fig. 1,119, which depicts two oscillagrams, the upper being the oscillagram of the alternating P.D. and the lower that of the current which passes. The maximum (semi-amplitude) value of the P.D. is 180 volts, and the maximum ordinate of the unidirectional current is 230 milli-amperes.

Fig. 1,119.—Voltage and Current Curves of a "Kenotron" (full temperature).

The kathode in this case was hot enough for the voltage to produce its full effect. If the kathode be not sufficiently hot the current produced is of the type shown in the lower curve in Fig. 1,120, in which the raising of the P.D. above 90 volts produces no additional current. This is due to the fact that the rate of emission of electrons from the kathode depends on the temperature, and as the current is entirely due to the transfer of electrons when the maximum emission corresponding to the temperature is reached, no additional current can be obtained. The bulb is, as a matter of fact, so highly exhausted that a steady unidirectional voltage of 100,000 or 150,000 volts produces no gaseous discharge. We cannot here pursue this interesting part of the subject further.

Fig. 1,120.—Voltage and Current Curves of a "Kenotron" (temperature low).

One method of making the electrical connections for the alternating current to be rectified and for the currents which are to keep the kathodes hot is shown diagrammatically in Fig. 1,121. The alternating current be rectified is produced in the [illegible] vo kenotrons are used, one of which will pass the half [illegible] the zero position, and the other the opposite half-waves. The arrang[illegible] ent is electrically similar to the double anode mercury-arc rectifier [illegible] ase, but in this case there must be two kathodes, the anodes and athodes being practically in parallel with each of the parallel links ntaining half of the coil supplying the alternating currents. In this iagram the anodes are represented by the flat lines A and A^1, and the athodes by the curved lines F and F^1, each of which, it should be noted s in circuit with a small battery and an adjustable resistance, the object of these circuits being to supply the currents which are to heat up the kathodes to the necessary temperature. The condenser C placed [illegible] the leads of the unidirectional current reduces the amplitude of the pulsations, and when it is of the proper magnitude the fluctuations of a 100 milli-ampere current have been found to be less than 5 per cent.

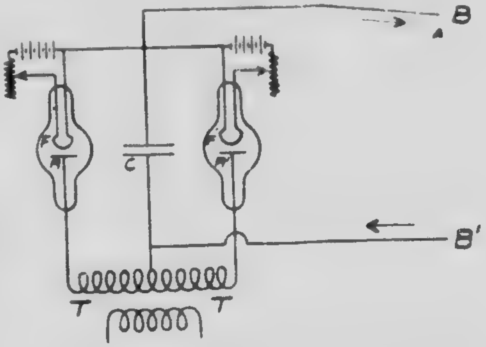


Fig. [illegible].—Co[illegible] Ke[illegible]
Half-wave Alternat[illegible]

Kenotrons have been constructed to give currents as high as 1·5 amperes (1,500 milli-amperes), but for commercial purposes the maximum is about 250 milli-amperes, at voltages up to 100,000 volts, or about 25 *kw*. The voltage drop in the kenotron itself when rectifying such currents, of the above order, is from 100 to 500 volts, and it therefore cannot be used in low-voltage circuits.

Gas-filled Rectifiers.—The vacuum in the Kenotron, as already mentioned, is extremely high, and it is found that the presence of small quantities of most gases has a marked effect upon the phenomena, in many cases cutting down the electron emission to a small fraction of that obtainable in a high vacuum, and causing also at low pressure the disintegration of the kathode. Inert gases and vapours are found, however, to have apparently no effect upon the electron emission if the kathode be made of pure tungsten. Experiments were therefore made with argon, which is the most inert gas known. The conditions of successful operations were carefully investigated, and a hot-kathode rectifier filled with argon was described by Mr. G. S. Meikle in the *General Electric Review* in April, 1916. These rectifiers all had tungsten kathodes, but many other materials were found to be suitable for anodes. Currents as high as 80 amperes were drawn from such rectifiers, the tungsten filaments being 20 mils in diameter.

The Tungar Rectifier.—In March, 1917, the rectifiers shown in Figs 1,122 and 1,123 were announced. The kathode is a close spiral of tungsten wire stretched between the two lower tungsten leads, which, passing through the glass, are attached to the screw-socket terminals in the usual way. Facing this spiral is a block of graphite of relatively large cross section, which acts as an anode and which is carried by a tungsten lead which passes through the glass. Fig. 1,122 is a two-ampere bulb, which is about 2 inches in diameter and between 5 and 6 inches long. Fig. 1,123 shows a six-ampere bulb, known as a *tungar* rectifier, and which is about 3 inches in diameter and 7 to 8 inches long. The bulbs have been carefully exhausted to the highest possible vacuum and then filled with very pure argon. Certain impurities, if present in even very small quantities, produce a marked disintegrating effect on the kathode, and also affect the working voltage. Purifying substances are therefore introduced in the form of a wire ring on the anodes, and when the tube is started these purifiers are volatilised and absorb the deleterious foreign gases, leaving the resultant argon gas remarkably pure.

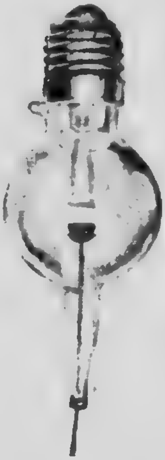


Fig. 1,122. — Two-ampere Tungar Rectifier.

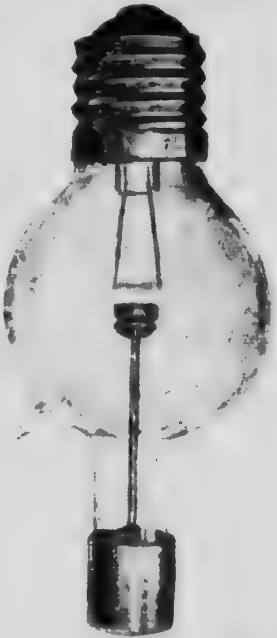


Fig. 1,123.—Six-ampere Tungar Rectifier.

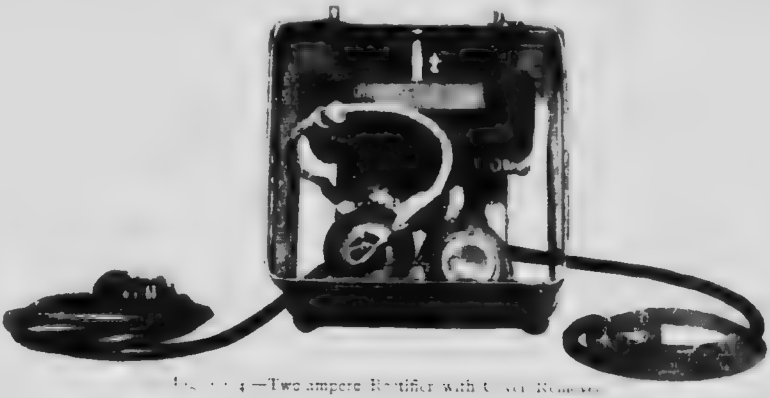


Fig. 1,124.—Two-ampere Rectifier with Cover Removed.

The Tungar is obviously a half-wave rectifier, and two must be used both half-waves are to be rectified. When first brought out only half-ve outfits were placed on the market for the purpose of charging the nall batteries used for lighting and starting petrol-driven automobiles. A two-ampere tifier set with cover removed is shown in [illegible] 1,124, and a diagram of the connections given in Fig. 1,125. It is designed to w current from 115 volt 60 ~ mains by [illegible] the ordinary lamp sockets (Fig. [illegible], the battery to be charged being ttached to the leads marked + and —. [illegible] alternating current passes through an [illegible] reactance, and the tungsten filament *f* of the rectifier is heated by 2·5 [illegible] from the coil. The overall dimensions the case are 5¾ inches by 6¼ inches 8½ inches high, and the [illegible] set weighs 8 lb. It will charge three cells with current of 2 amperes.

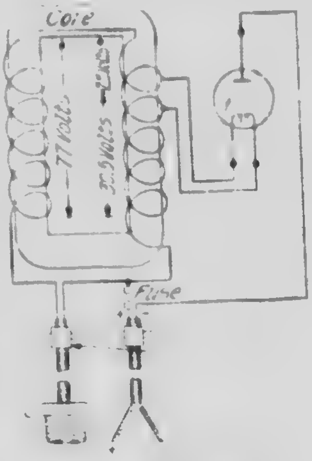


Fig. [illegible] Connections of the Tungar Rectifier

The other standard size is the 6-ampere 75-volt rectifier, which will charge up to 30 cells with from 1 to 6 amperes. The complete set in this case measures 10¾ inches by 12¼ inches by 11 inches. The efficiency when charging thirty cells is 75 per cent.

III. ELECTROLYTIC RECTIFIERS

The principle of these, as explained in Vol. I. (*see* page 568), is that if an aluminium electrode be immersed in an alkaline electrolyte an electric current can pass readily from the liquid to the metal, but not from the metal to the liquid, owing to the formation, electro-chemically in the latter case, of a film of oxide of high resistance. Such an aluminium electrode can therefore, in practice, only act as a kathode. If, therefore, the other electrode of an alkaline voltameter be some indifferent metal (e.g. steel)—and an alternating P.D. be set up between the electrodes, only the half-waves in one direction can pass, and the opposite half-waves will be suppressed.

In the historical section the Gratz arrangement by which four such voltameters can be grouped to form an "electric valve" is described, and an early form of such a valve, the "Nodon" valve, is illustrated.

As a piece of electro-chemical apparatus the Nodon valve is interesting, but for technical use it had serious defects which it has been the object of subsequent inventors to overcome. The most serious of these defects were (i.) the heating of the electrolyte during use, leading to the deterioration and ultimate failure of the valve; (ii.) the necessity for using four cells; and (iii.) the low efficiency.

In modern types of electrolytic rectifiers the necessity for using four cells has been overcome by adopting the same general system of electrical connections as is used in the mercury-arc and hot-kathode rectifiers.

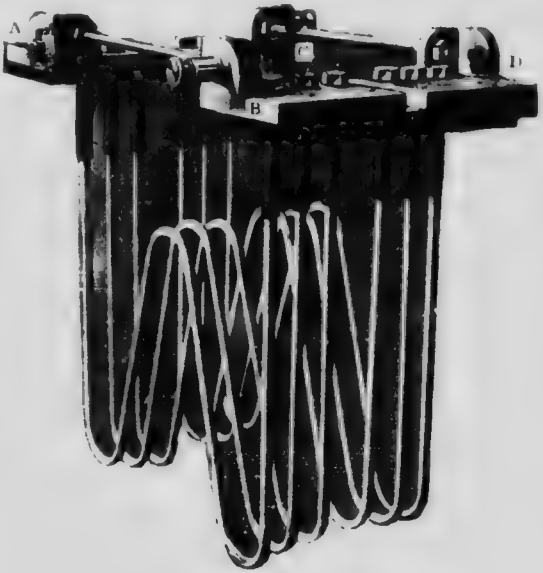


Fig. 1,126.—The Kathode Element in the Grid Rectifier.

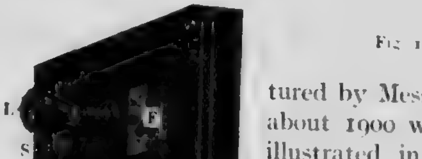


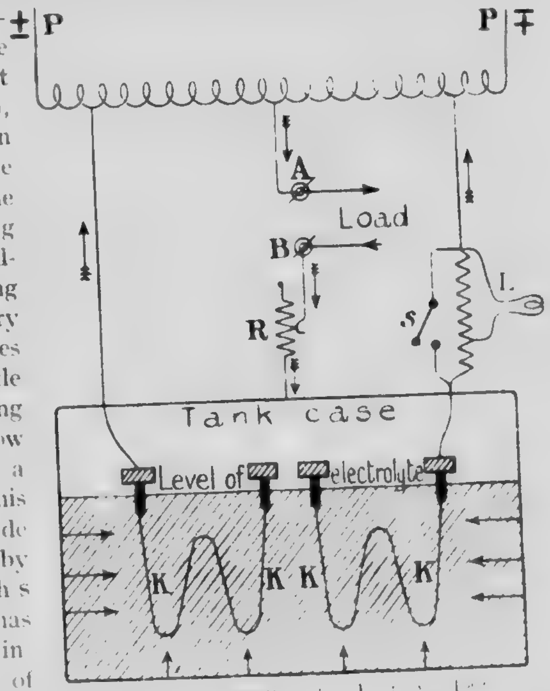
Fig. 1,127.—Electrolytic Rectifier and Switch Panel.

The Isenthal Grid Rectifier.—One of the most recent types of electrolytic rectifier is that manufactured by Messrs. Isenthal and Co., of London, who about 1900 were the makers of the Nodon valve illustrated in the historical section (*see* Fig. 549, Vol. I.). The electrolytic apparatus is contained in a single steel tank, and the kathode element now takes the form shown in Fig. 1,126. The basis of the element is an aluminium rod of **W** shape, which is connected to terminal blocks on the outside of the containing tank, and has its extremities protected at the upper level of the electrolyte by ebonite sleeves which prevent corrosion as the level of the liquid rises and falls. Six rods are shown arranged, three in parallel, in two groups between terminal blocks A, B, C and D, the two groups forming two sets of kathodes.

These kathodes are immersed in an alkaline solution, such as carbonate of soda, contained in the solid seamless steel tank (seen in

Fig. 1,127), which acts as the anode. Internal partitions projecting upwards between the **W** rods have been tried and found to offer no practical advantage. The tank is placed on a wooden tray, which is supported on porcelain insulators.

The simplest outfit is that shown in Fig. 1,127, the electrical connections being as depicted diagrammatically in Fig. 1,128. The kathode elements are connected as shown across the greater part of the coil of the static auto-transformer, which is mounted on the back of the lower part of the panel (Fig. 1,127) and between it and the electrolytic tank. The load is to be connected to the terminals A B, which are placed at the lower part of the board (Fig. 1,127), and are electrically between the middle point of the transformer coil and the anode tank. For starting purposes, to prevent a sudden rush of current during the brief period necessary for the aluminium surfaces of the kathode to settle down into proper working conditions, a carbon glow lamp L in parallel with a resistance is inserted in this circuit on one of the kathode leads, but is cut out by the short-circuiting switch S when the steady stage has been reached. This is indicated by the dimming of the lamp, which at first glows brightly. The other fitments on the board are the D.P. main switch M and the D.P. fuse F, which are in the primary circuit of the transformer.



[illegible]

The principle of working will be understood from the previous descriptions of other rectifiers, and by noting that current can only pass towards the kathode rods K K (Fig. 1,128), and not in the opposite direction. Thus one set of half-waves is supplied by the P.D. of one half of the transformer coil, and the other set by the other half. The load current is pulsating, the number of ripples per second being double the periodicity of the supply current, but the amplitude of the fluctuations will depend, as usual, on the character of the load, and will be much diminished by a well-chosen inductance in the load circuit.

A more complete outfit for dealing with more numerous conditions of load is provided on the panel shown in Fig. 1,129, in which, in addition to the apparatus indicated in Fig. 1,128, there is a multiple D.P. switch P, with its studs connected to different tappings on the coil of the transformer, and by which the voltage supplied to the load can be varied. There is also a rheostat R for adjusting the current in the load circuit, and a voltmeter and ammeter are provided. The ammeter is in the load circuit, and the voltmeter, by means of a voltmeter switch, is connected to measure the voltage supplied to the load.

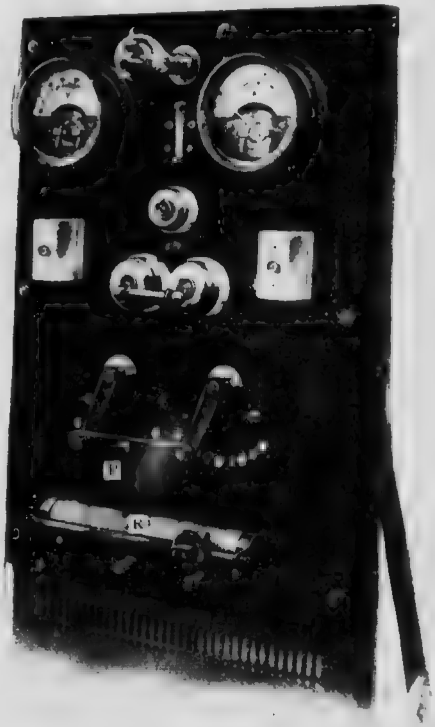


Fig. 1,129.—Regulating Panel for Electrolytic Rectifier.

The maximum current available depends upon the size of the electrolytic element. Three standard sizes are made of 5, 10, and 20 amperes respectively, the weights of which vary from 109 to 150 lb. for the smallest size, from 200 to 256 lb. for the 10-ampere size, and from 300 to 350 lb. for the 20-ampere size. The characteristics of the 10-ampere size for different voltages are given in Fig. 1,130. The characteristic, as might be expected, is a drooping one, especially for high voltages, when the full voltage of the transformer is being used. For low voltages it becomes fairly steady above 20 per cent. of full load. Some of the curves show over-loads, curve A going as far as 50 per cent. over-load, but such overloads must necessarily lead to greatly increased heating, and probably to a much more rapid deterioration of the kathode. The design, however, is such that new kathode elements, which are supplied by the manufacturers ready for use, can be easily installed. Owing to evaporation, the electrolyte must be replenished with distilled water from time to time, the standard level being one inch above the lower ends of the ebonite protectors. The efficiency of the rectifier, including the losses on the auto-transformer, is from 55 to 60 per cent., which, at

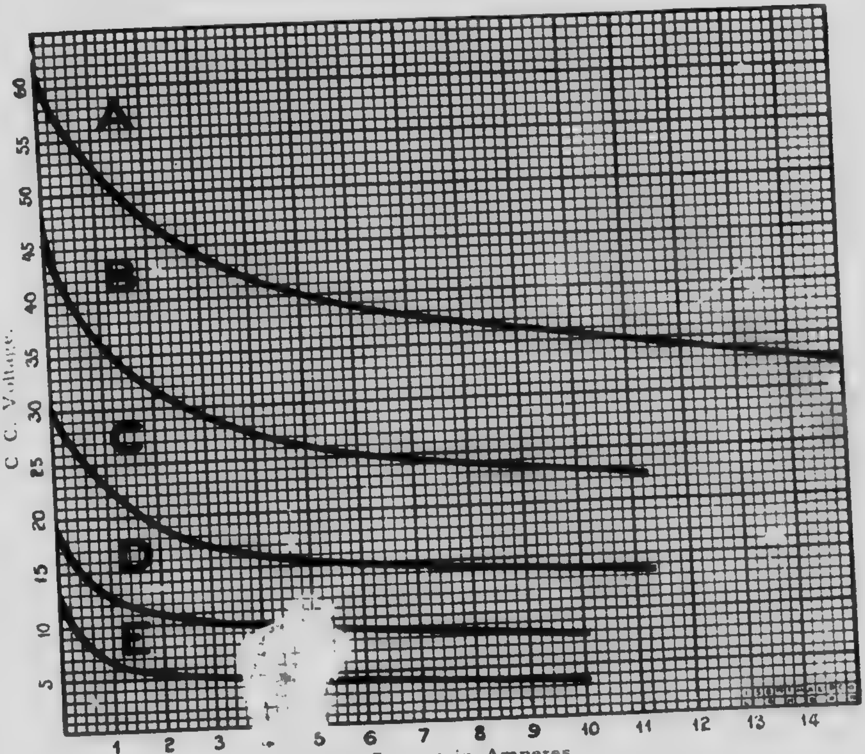


Fig. [illegible].—Characteristic Curves of a 10-ampere Electrolytic Rectifier

first sight, appears to be somewhat low, but it should be remembered that, when working, this type of transformer needs but little attention, a point not to be overlooked when considering the commercial aspect of its utilisation.

CHAPTER XI

THE TRANSMISSION AND DISTRIBUTION OF ELECTRIC ENERGY

THERE is, speaking generally, no hard and fast dividing line between the use of the terms "*transmission*" and "*distribution*" of energy by electrical methods. In practice, however, there are two classes of problems which call for somewhat different treatment. There is the case where energy has to be distributed to a more or less numerous body of consumers in a restricted area from a position in or near the area where there is either a generating or a sub-station. To this case it is convenient to apply the term "distribution." When, however, the distributing point is a sub-station, the energy has to be conveyed to that sub-station from a generating station, a longer or shorter distance away, and to such cases the term "transmission" might well be confined. An overlap occurs where feeders are used in a distributing system, such feeders being, in effect, subsidiary transmitters. Their use allows the boundaries of the distribution area to be extended.

In a brief chapter in Vol. I. (Chapter XV.) the fundamental principles underlying the economical transmission of electric power over long distances have been explained, and the various systems available have been described, the technical details being postponed for this section. It has been there shown that the higher the voltage used in the transmission lines, the higher the electrical efficiency of transmission, and we have now to deal with the considerations which limit as an engineering proposition the voltage available in various cases of transmission, and the appliances and apparatus devised to meet the practical problems which arise. The various types of transformers available for raising and lowering the voltage as necessity arises were scheduled in the chapter cited, and in the preceding chapters of this volume we have described in full detail such of these transformers as are used in modern work. Their peculiarities and limitations must be borne in mind.

Methods and Systems.—It will be convenient at this stage to draw a distinction between the "method" of transmission or distribution and the electrical "system" adopted. Thus the electrical system may utilise either alternating or continuous currents or both, and in the case of the former the currents may be monophase or polyphase with two, three, r more phases. In due course we shall deal briefly with the relative merits of these various systems in connection with the general and special problems presented. But whatever "system" be adopted, two or more conductors are required between the place where the electrical energy is generated and the place, either intermediate or final, where it is handled or utilised, and these conductors must be erected, or laid, and insulated. The "methods" of doing this, whether by bare wires carried overhead or by carefully insulated underground cables or otherwise, are to a great extent common to all the systems, and can be conveniently considered apart, although there are certain problems in which one affects the other. We propose to describe the methods first, but would again remind the reader that economical transmission over long distances can only be obtained by the use of high voltages, a matter to which we shall return when taking up the question of "systems."

General Methods Available.—Both for transmission and distribution there are two quite distinct methods available, namely "overhead" and "underground." The relative merits of these will appear in the sequel; but, speaking quite generally, it may be said that the overhead method, in which a conductor, usually bare, is carried above the ground at a safe and convenient height, is most widely used for "transmission" purposes, more especially when the distances are great. On the other hand, for distribution schemes, especially in populous districts, the "underground" method is more frequently adopted. In it the conductors, surrounded by proper insulating material and properly protected, are laid underground in conduits or otherwise. In both cases, however, there are quite numerous exceptions, depending on the special conditions of the particular case. Again, speaking quite generally, it may be said that "overhead" circuits are the cheaper and underground circuits the more costly, but there are exceptions even to this statement.

Before, however, describing in detail any of the methods referred to, a brief reference to the materials available for the conductor will be useful.

I.—THE CONDUCTOR

Copper *v.* Aluminium.—Of the various metals whose specific resistances are tabulated in Vol I. (*see* page 751), only two—copper and aluminium—are, from a consideration of their physical properties and cost of production, serious competitors as conductors for the electric transmission of power. Silver, which is a slightly better conductor than copper, is ruled out on account of its cost. Iron or steel, which is considerably cheaper and stronger than either copper or aluminium, has unfortunately a high resistivity, and is readily corroded, besides having high inductive impedance in A.C. working. Copper-clad steel wire is, however, now being used for special work, and its use may develop.

rapidly. Aluminium, because of the prohibitive cost of production, was no seriously in the running until towards the end of the last century, when, a already mentioned in Vol I. (*see* page 271), its price was reduced from a average of 20s. per lb., at which it stood between 1862 and 1888, to les than 1s. 6d. per lb., and during this century crude aluminium in quantit has been quoted at less than £100 per ton, or, say, 10½d. per lb.

A reference to the table cited shows, however, that aluminium has a much higher specific resistance than copper (about 1·7 times), but this disadvantage is redressed to a great extent by its lower density, which is only about 30 per cent. of that of copper. Specific resistance, it will be remembered, only takes account of the *dimensions* of the material. Taking the density, however, into account, we find that of two wires of equal length and weight the resistance of the aluminium wire will be 0·51 of the resistance of the copper wire. The disadvantage is that the aluminium wire will be thicker. The physical constants of the two metals may be tabulated as follows :—

TABLE XIV. PROPERTIES OF COPPER AND ALUMINIUM COMPARED.

Property.		Copper.	Aluminium.	Ratio $\left(\frac{\text{Copper}}{\text{Aluminium}}\right)$
Specific electric resistance at 0° C. ...	soft	1·561	2·665	·585
Do. do.	hard	1·647	2·768	·595
Specific gravity	soft	8·78	2·56	3·43
Do. ...	hard	8·95	2·71	3·30
Weights of equal length and resistance		1·0	0·51	1·96
Coefficient of linear expansion (1° C.)		·0000167	·0000234	0·714
Thermal conductivity		1·0	0·425	2·35
Specific heat		·094	0·212	0·443
Modulus of elasticity (lbs. per square inch)		16 × 10^6	9 × 10^6	1·8
Tensile strength		40–60,000	20–30,000	2·0
Atomic Weight		63·2	27	-

The above are the outstanding facts regarding the two metals; their influence on practical problems will be dealt with as these arise.

In America, in order to strengthen an overhead aluminium conductor to enable long spans to be used, a steel core is inserted. Examples will be given later, but the practice does not find favour in this country.

Form of the Cross-section.—The two factors which affect the resistance of a conductor are the length and the area of the cross-section. In transmission problems the length required is practically fixed by the distance between the extreme points and the route available. The area of the cross-section will be decided by considerations partly dealt with above, but the geometrical shape of the cross-section must be determined by the circumstances of the particular problem.

For continuous-current transmission the form of the cross-section does not affect the resistance; but in alternating current work, as shown elsewhere, it may become important, especially at high periodicities, because of the "skin" effect. For many purposes a circular section suffices, and is convenient to manufacture and to handle. Such a section has the smallest periphery for the area enclosed (*see* page 23), offers the least resistance to the wind in overhead work, and gives the smallest surface to be covered with insulating material in underground work. It is, therefore, in practice almost universally adopted for transmission lines, but for the more complex distribution problems of A.C. transmission other forms of cross-sections are sometimes preferable.

Stranded Conductors.—The necessary cross-section of the material circular or otherwise, is obtained with a minimum of space by rolling or drawing all in one piece. But in dealing with large quantities of electric power the required cross-section may be so large, e.g. a square inch, that the conductor so produced will be rigid and devoid of flexibility. It will, therefore, be difficult to handle, erect, or lay. To meet this drawback, conductors of even a moderate cross-section are *stranded*, that is the conductor consists of a number of separate wires laid together, and making up between them the required cross-section of material. Illustrations of such stranded conductors are given in the following pages; the device ensures the necessary flexibility, and on that account alone secures that the total cost of the completed circuit is reduced.

An electrical disadvantage is that the *resistance is increased*. It is obvious that the best method of making the various strands lie well together and occupy a minimum of space is to twist them round one another as is done in so many other similar industrial cases, e.g. the manufacture of cotton thread. Such compound conductors are usually known as "cables," and the length of a complete twist is referred to as the "*lay*" of the cable; it may be anything from 6 inches upwards. Now, when an electrical current enters such a conductor it divides, if it be a continuous current, probably in equal parts, amongst the similar strands of the conductor, and although the conductors are touching and are not purposely insulated from one another, each separate current, for all practical purposes, remains in its own strand throughout the length of the cable. This is because (i.) the conductors, if circular, only touch along lines, and (ii.) the surface resistance, owing to the formation of thin layers of oxides and dirt, is greater between the strands than is the resistance of the continuous solid metal in the interior of each strand. The net result is that each current, in general, pursues a spiral path of greater length than the length of the cable as a whole, and this effective increase in the length of the path correspondingly increases the resistance. The amount of increase depends upon the "lay" adopted. For uniformity and convenience the rule laid down by the Engineering Standards Committee is that the standard lay shall be such as shall involve "an increase of 2 per cent. in each wire except the centre wire for the total length of the cable." The resistance and the weight of standard stranded conductors are, therefore, 2 *per cent. greater* than unstranded conductors of the same cross-section and length.

The *number of strands* in any given case depends upon the cross-section and the degree of flexibility required. A number, however, is always selected in modern practice which will give to the stranded conductor an outer contour as smooth as possible. To satisfy this condition the standard numbers of separate wires are 1, 7, 19, 37, 61, 91, 127. It will be noticed that these numbers form a series in which the *difference* between successive terms increases by six. A 127-strand conductor is the most subdivided one scheduled by the Engineering Standards Committee, and it may interest the reader to learn that when formed of copper wire 0·101 inch in diameter the weight per mile of the conductor alone is 21,120 lb., or nearly 9½ tons. Very small strands of three or four wires are sometimes used.

It may be convenient to add here that the rules of the Engineering Standards Committee allow a *variation* of 2 per cent. from the adopted standard of resistance in all conductors. Rubber insulated copper conductors should be *tinned*, for reasons given subsequently; 1 per cent. increase of resistance is allowed for such wires for diameters between 0·118 inch and 0·028 inch inclusive, i.e. Nos. 11 to 22 S.W.G.

We pass now to the description of and the problems connected with various practical methods of transmission, and shall take the "overhead" methods first.

II.—OVERHEAD LINES

For long distances and high-voltage *transmission* work the running of the conductors overhead, suitably insulated on suitable supports, practically holds the field from the point of view of capital cost, though occasionally short lengths of underground cable may have to be introduced into the line owing to special conditions. In short-distance *distribution* systems, though underground work is more common, overhead work sometimes offers a good practical or even the best solution, as, for instance, in electric traction and in certain special cases, one or two of which are referred to below.

The principles and details of construction of overhead lines not dealing with large quantities of electric power are most conveniently dealt with in connection with the subject of telegraphy and telephony (*see* relevant chapters), and overhead circuits for electric traction work are best considered in connection with that work (*see* pages 1383 to 1424). In addition, electric transmission at moderately high voltages is also most conveniently considered as leading up to transmission at very high voltages, which is sufficiently important to claim a separate section (*see* pages 1118 to 1141). The descriptions in this section are therefore confined to a few special cases not coming under any of the above headings.

Overhead transmission is often the only kind of transmission which is commercially possible even for comparatively short distances and moderate voltages, such as the supplying of electric power from a conveniently placed generating station to a group of collieries, none of which is more than a few miles distant. In addition to a material saving in the cost of construction, it is often easier to obtain the way-leaves for an overhead line than for underground conductors in trenches, although the latter, being out of sight, do not interfere with the amenities of the countryside.

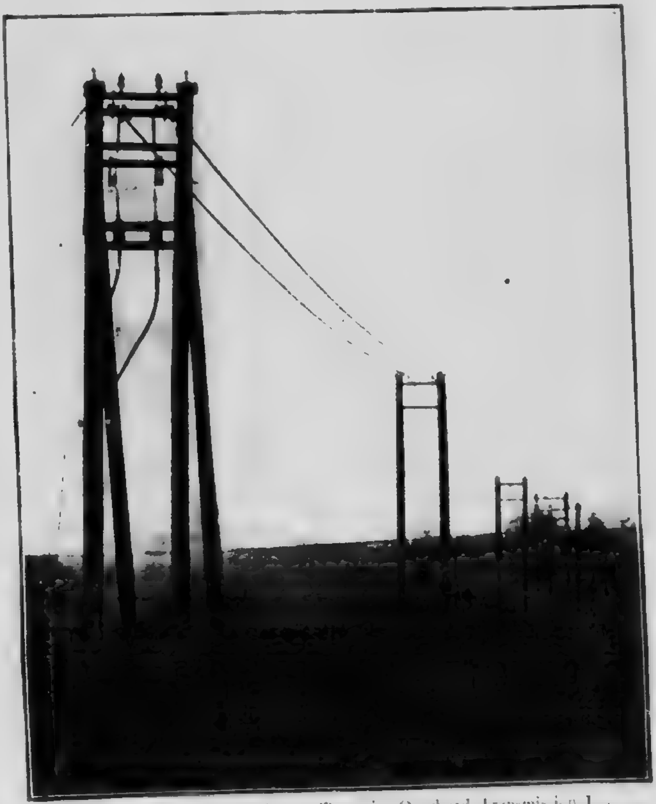


Fig. 1,131.—Colliery 600-Volt c.c. Two-wire Overhead Transmission Line.

Two general examples of such transmission will suffice here. In Fig. 1,131 there is shown a two-wire line for transmitting power from the Rockingham Gasworks power house to the Tankersley Park Colliery. The circuit is for continuous currents at 600 volts, and the line, consisting of two wires, is carried on insulators supported on a crossbar at the top of two parallel wooden poles. The poles in the foreground are a terminal set where the overhead line is interrupted or terminated, and these poles are therefore securely strutted and stayed. The construction at the other poles is lighter. The conductors are of aluminium 1·4 square inches in section, and the maximum load is about 700 amperes, transmitting about 4. kilowatts. The cost per mile was about £1,200. If equivalent coppe conductors had been used the cost, at the price of copper prevaili at the time of erection, would have been £1,800 per mile, and the line had been carried underground with insulated and armour aluminium cables the cost would have been £2,200 per mil

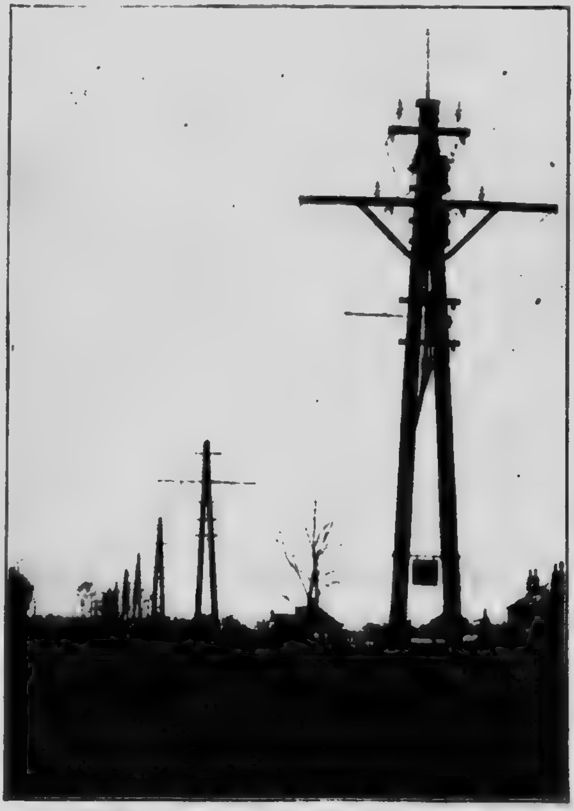


Fig. 1,132.—3,000-Volt Three-phase Overhead Lin

The second exampl (Fig. 1,132) is that o a three-phase four-wir line erected in 1911 by the War Office a Aldershot. The pressure was 3,000 volts between phases, the fourth line being the neutral wire. Here again the terminal pole is shown in the foreground, the transmission at this point changing from underground to overhead. The underground cable passes up one of the poles to a terminal sealing-box, whence wires pass through kicking coils to the overhead lines. The lightning arresters are also shown. The poles are of the A type, there being two cross-arms, each carrying two wires. The lower cross-arm is considerably lengthened to carry a cradle guard, the details of which can be readily made out in the figure. This guard, as explained elsewhere, is for the purpose of catching and earthing any broken high-voltage conductor.

The above examples will give some idea of the general methods adopted for carrying bare conductors for electric power transmission when the voltages are not excessively high. A few of the details may now be more fully described.

Poles and Cross-Arms. On lines on which the weight of the conductors is not too great or the spans too long, and where the voltages of transmission are moderate, the supports used follow more or less closely the practice on telegraph lines on which, when heavily loaded, the mechanical conditions are very similar. This practice is very fully dealt with in a subsequent section on telegraphy, to which reference can be made. The similarity will be evident from an inspection of the poles shown in Fig. 1,133, in which except for the small number of wires carried, the lines appear to be very similar to telegraph lines. The pole in the foreground which is at a point where there is a bend in the route, is heavily stayed whilst farther on in the straight are ordinary simple poles.

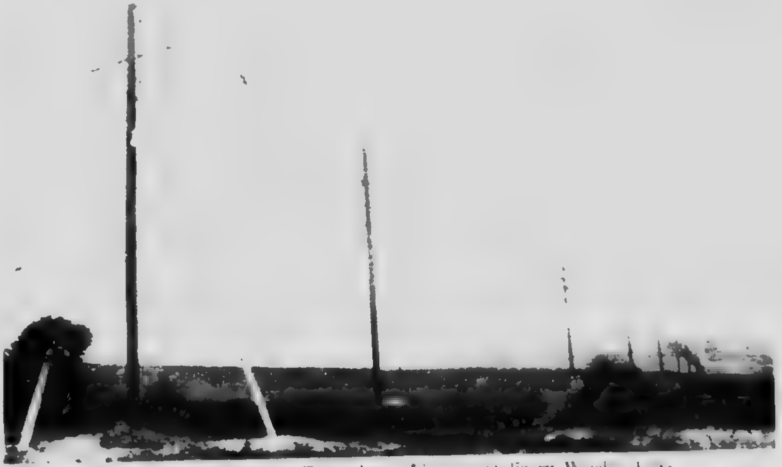


Fig. 1,133.—High-voltage Transmission Lines on Ordinary Wooden Poles.

Where the overhead line ends good telegraph practice is also followed, as is shown in Fig. 1,134, in which two three-phase overhead lines are terminated on substantial H poles, and the transmission transferred to underground cables which are brought up to trifurcating heads supported on cross-arms below the last cross-arms of the overhead lines. Note should be taken of the stays which counteract the pull of the overhead wires, and also of the cross-stays and struts between the poles.

The material of the poles and cross-arms may either be wood or steel, the choice in a particular case being determined by financial considerations of the whole cost, including not only the first cost but the upkeep or maintenance charges. If for local reasons the spans must be short, say not exceeding 80 or 90 yards, wooden poles are usually cheaper both for first cost and maintenance. Where long spans can be used steel poles oft a better solution except in smoke-laden [illegible] districts, where the cost of upkeep in painting, etc., becomes prohibitive if the poles are to be kept from deteriorating rapidly.

Where the mechanical conditions are too exacting for ordinary telegraph construction practice, the design of the supports is carefully worked out for the particular case. Details of some of the solutions will be found in the next section (see pages 1118 to 1141) on extra high-voltage transmission.

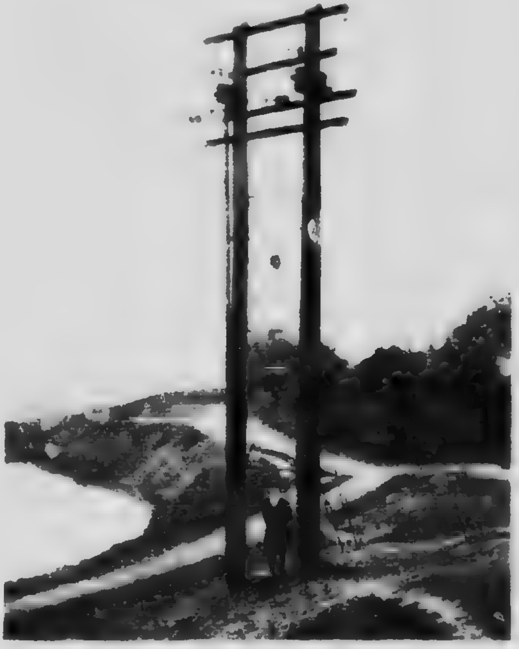


Fig. 1,134.—Terminal Pole for Two Three-phase Lines.

There are many cases, especially in the outskirts of large cities and in sparsely inhabited districts, where the cost of running underground conductors is not justified by the load to be distributed, and where, therefore, the alternative of overhead distribution may well be considered and adopted. In such cases, the question of the material used for the support may become a determining factor both from the point of view of cost and æsthetics. It may be conceded at once that any overhead construction for stringing wires along streets and roads has [illegible] elements of unsightliness which cannot be eliminated, but with [illegible] selection of material and [illegible] the supports the unsightliness may be reduced to a minimum, or even a mildly ornamental and pleasing effect may be produced. [illegible] poles, which at one time would have been universally adopted, are becoming scarce, and in many places their cost is high and increasing. Moreover, at the best, and when loaded with wires, they are [illegible] unsightly. Much better are the tapered steel poles illustrated [illegible]where, which are much more elegant, and are practically indestructible. Even they, however, may in certain cases be too costly to be seriously considered.

Concrete Poles.—An alternative material [illegible] of late years is reinforced concrete poles made [illegible] certain cases at a cost not exceeding [illegible] poles can be given a neat [illegible] [illegible] if only [illegible] fittings [illegible] carefully de[illegible] [illegible] [illegible] ments [illegible] may be attained [illegible] considerations [illegible] space [illegible] [illegible] the [illegible] will be evident [illegible] electrical engineer to the [illegible] of the material for poles pre[illegible] difficult problems. In Fig. [illegible] concrete pole is shown in [illegible] manufacture. The part shown [illegible] part of the base, which is to [illegible] in the ground, the plinth which appears above the ground line, and part of the chief body of the pole. The appearance of the top of the pole can be gathered from Fig. 1,136, which is a line drawing of the top with various fitments not only for the power lines, but also for telephone lines and the electric lighting of the street.

Fig. 1,13[illegible] [illegible] Concrete [illegible]

[illegible] of a Concrete Pole.

Insulators.—The insulators used for moderate and high voltages are similar to the stronger patterns described and illustrated in the telegraph [illegible]. For the higher voltages some of the simpler forms of insulators as developed for extra high-voltage transmission are [illegible]ble, and may be briefly referred to here.

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* Vol. LXXV. (1914), page 601.

The most obvious method of increasing the effective insulation of a ordinary pin insulator is to increase its size, especially in the direction of th length of the surface over whic surface leakage occurs. As pointe out elsewhere, it is not the direc leakage through the material which is troublesome in ordinary cases, but the leakage from the line wir to the bolt over the outer surface. In fact, it is to guard against this leakage that the ordinary form was evolved, so as to provide a sufficient amount of protected surface which could be depended upon to remain dry in wet weather. By increasing and altering the relative dimensions additional protected surface can readily be obtained, it being borne in mind that what is to be aimed at is to increase the length of the protected path from the uninsulated metal pin to the nearest point of the exterior exposed surface of the insulator which is in contact with the live wire.

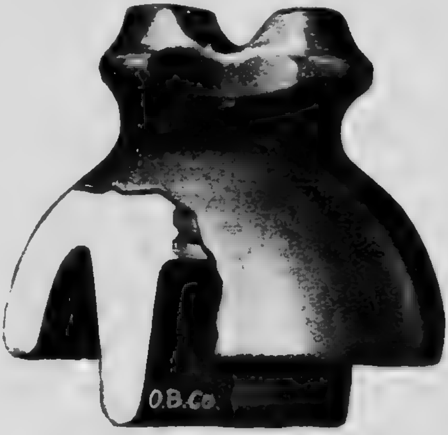

Fig. 1,137.—Double-shed Porcelain Insulator for 11,000 Volts.

Beyond altering the absolute and relative dimensions, a direction in which the length just referred to can be increased is by introducing additional corrugations into the protected path, and in following out this idea the "double-shed" and "triple-shed" insulators for telegraphic work described elsewhere have been evolved. An example of a double-shed insulator for a transmission line is given in Figs. 1,137 and 1,138, the latter being marked with the principal dimensions. It is claimed that this insulator, which

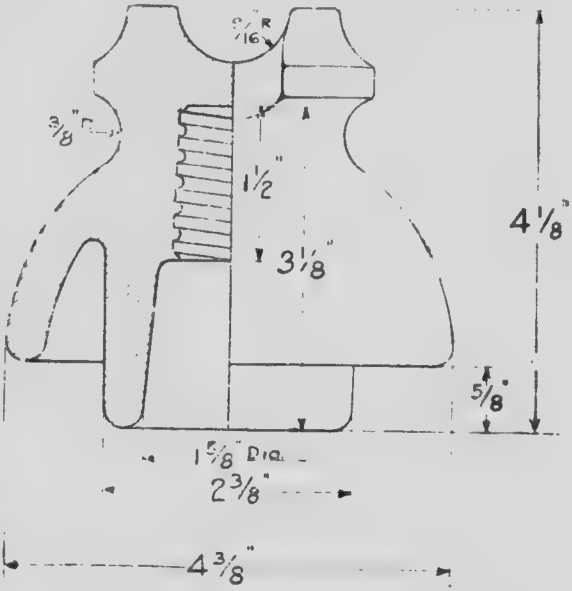

Fig. 1,138.—Dimensions of Double-shed Insulator for 11,000 Volts.

manufactured by the Ohio Brass Company of Mansfield, Ohio, will stand line voltage of 11,000 volts, the test voltage during manufacture being 40,000 volts. In this insulator, and those developed from it, the line wire lies in the top groove, and is held fast by binding wire or strip lying in the side groove, as explained elsewhere.

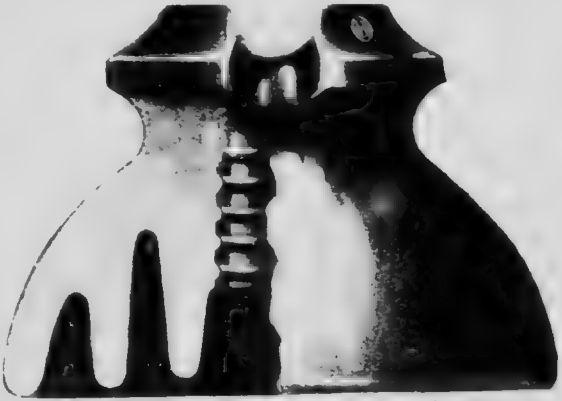

Fig. 1,139. [illegible] Volts.

The idea is carried still farther in the triple-shed insulator, of which an example is given in Figs. 1,139 and 1,140, the former being as before, partly an external and partly a sectional view from a photograph of an actual insulator, and the latter a dimensioned sketch partly in section. The bell of this insulator is very little larger than that shown in Fig. 1,137, but the protected leakage surface has been increased. It is intended to work with a line voltage up to 13,000 volts, and is tested to 50,000 volts.

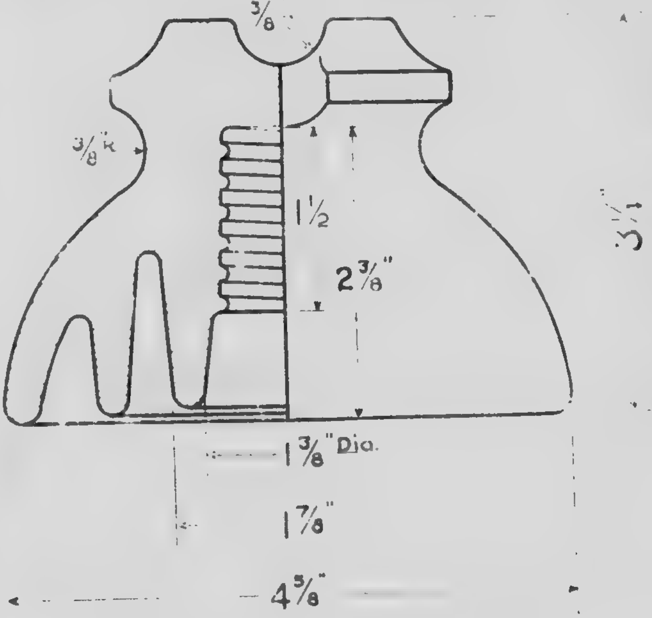

Fig. 1,140. Dimensions of Triple-shed Insulator [illegible]

Sag of the Wires. — The "sag" or "dip" to be allowed in tightening up a wire stretched between two supports in the same horizontal plane is a practical question which was exhaustively studied in connection with the erection of telegraph lines years before overhead transmission of electric power became an engineering subject The underlying principles are dealt with in the section on telegraph line construction, and are the same in the power transmission case.

Without undue repetition, it may be mentioned that the formula used for the calculation of the sag or dip (d) when the tension (T) is known is—

$$d = \frac{l^2 w}{8\,\mathrm{T}} \qquad . \quad . \quad . \quad . \quad . \quad . \qquad \text{(1}$$

where w is the weight per unit length of the conductor and l is the horizontal distance apart of the supports. The units of length and force used must be the same throughout. For instance, if the length be in feet and the force in lbs.-weight, then d is the sag measured in feet for a given tension T in lbs., w being the weight of the wire in lbs. per foot.

This formula is approximately true only, but is sufficiently near for the cases which usually occur in telegraphy. The curve to which it strictly applies is a *parabola*, with its vertex at the lowest part of the loop. The true curve, however, is that known to engineers as the *catenary*, which is the curve in which a perfectly flexible gravitating cord hangs when supported at its two ends. The difference between the two curves is practically inappreciable in the short spans used in telegraphy, but in the longer spans used sometimes in power transmission the catenary formula—

$$d = \frac{\mathrm{T}_0}{w}\left(\mathrm{Cosh}\frac{l\,w}{2\,\mathrm{T}_0} - 1\right) \qquad . \quad . \quad . \qquad \text{(2}$$

should be used. In this formula T_0 is the horizontal tension at the lowest point of the loop, and it is interesting to note that the tension in the curve close to the insulator is

$$\mathrm{T}_1 = \mathrm{T}_0 \,\mathrm{Cosh}\frac{l\,w}{2\,\mathrm{T}_0} \qquad . \quad . \quad . \quad . \qquad \text{(3}$$

Equation (2) allows the "dip" (d) to be calculated when a safe value is assumed for T_0. Both equations, however, require the use of a table of hyperbolic cosines ("Cosh"). Such tables were, not many years ago, difficult to procure, but, thanks to the energy of Dr. A. E. Kennelly and others, they are now becoming common amongst engineers.

Both the formulæ (1) and (2) show that the "dip" is independent of the gauge of the wire, but is dependent upon the material used. It also depends upon the maximum stress (i.e. lbs. tension per unit cross-section) to which it is considered safe to subject the wire.

Effects of Temperature.—As pointed out elsewhere, the dip also depends on the temperature and coefficient of expansion of the wire, and the usual formulæ for calculating this effect, as based on equation (1), will be found in the telegraph section. The formula for the length (L) of the wire based on equation (2) is—

$$\mathrm{L} = \frac{\mathrm{T}_0}{w}\,\mathrm{Sinh}\frac{l\,w}{2\,\mathrm{T}_0} \qquad . \quad . \quad . \quad . \qquad (4)$$

to which the usual equations for the linear expansion of the wire with rise of temperature can be applied. In this formula "Sinh" is the hyperbolic sine, and can be obtained at once by reference to the proper table.

Copper v. Aluminium.—On page 1102 we gave a table of the physical constants of these two metals, and we are now in a position to comment upon some of the effects of these constants in problems of overhead line erection.

As regards wires of equal conductivity, copper per unit length is nearly twice (more exactly, 1·96 times) the weight of aluminium, and therefore for equal tensions in the wire the sag for copper according to equation (1) would be twice that for aluminium. The tensile strength of copper is, however, about twice that of aluminium, and therefore with the same "factor of safety" the value for copper of T in the formula may, allowing for the larger cross section of the aluminium (1·65 : 1), be 1·2 times that of the value for aluminium, thus partly diminishing the relative sags to 1·7 : 1, when wires of equal conductivity and with the same factor of safety are compared. A greater value of the sag means that parallel wires at the same level must be spaced farther apart to avoid contact when swinging in the wind, and this means either more poles or increased height and cost of the poles, increased length of cross-arms, etc. The effect of the sag on the spacing of wires at different levels is also obvious. The net result is that copper lines of 0·10 sq. in. and under are usually the cheaper.

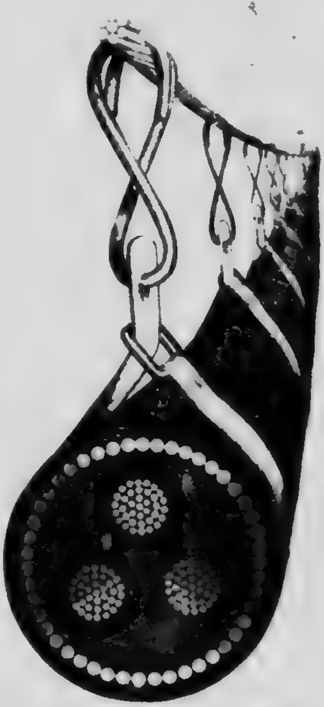

Fig. 1,141.—Threecore ·2 Square[illegible] Cable Suspended from Wire Rope

Another disturbing factor which complicates the comparison is the effect of the different coefficients of linear expansion with rise of temperature, the coefficient for aluminium being 1·4 times that for copper. This means that the sag of the aluminium wire will increase more rapidly than that of the copper wire as the temperature rises. The law connecting the sag with the rise of temperature is a too complicated one for treatment here, but corresponding to equation (1) above we have

$$d_1 = \sqrt{d^2 + \tfrac{3}{8} l^2 \theta k} \quad . \quad . \quad . \quad . \quad (5)$$

in which k is the coefficient of expansion and d_1 is the dip at a temperature θ degrees higher than that for which the dip is d. For the catenary curve, as already mentioned, the usual expansion formula must be applied to L in equation (4).

A change of atmospheric temperature, of course, affects the temperature of the wire, and for telegraphic purposes elaborate tables, referred to elsewhere, have been calculated for the sags of copper and iron wires for ordinary terrestrial temperatures. The results are striking. Thus for copper wire a sag of 2 ft. 2 in. at 22° F. for a certain span is doubled at 75° F., and becomes 5 ft. 0 in. at 100° F.

Ohmic Heat. The passage of a telegraphic current, however, does not appreciably heat the conductor, but in power-transmission problems the conductor becomes heated by the current sufficiently to affect the sag. Thus, according to Mr. B. Welbourn[*] a current of 267 amperes will, in still air, raise the temperature of a copper conductor 50° F. above the temperature of the surrounding air, and an aluminium conductor of the same conductivity will be similarly heated by a current of 304 amperes. In each case the sag of the wire will be increased, but more so in the case of aluminium than of copper. As in addition the aluminium wire is more affected by wind pressure, a subject into which we cannot enter in detail, copper is better than aluminium where the effect of change of temperature on the sag is important.

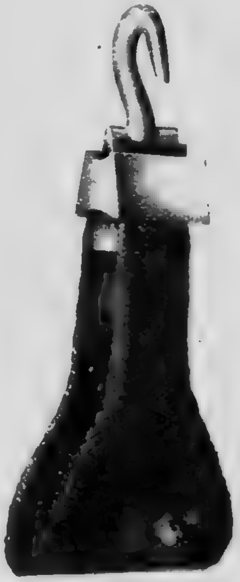

Fig. 1,142.

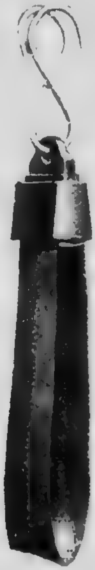

Fig. 1,143.

[illegible] Heavy and Light Types of Cable Suspenders.

Inductance and Capacity.—There are still two other factors to be taken into account in A.C. transmission—namely, the inductance and electrostatic capacity of the line, and in both these, owing to the greater size of the aluminium wire for equal conductivity, the values for aluminium are greater for equidistant wires than the corresponding ones for copper. Tables of these values will be found in Mr. Welbourn's paper referred to above.

Overhead Cables.—Heavy cables, as constructed for underground work, are sometimes for short distances more conveniently carried overhead than laid underground, such cases frequently occurring in colliery work between the generating station and the pit mouth. In these cases, where the distance is not too great, it is well to preserve the continuity of the cable down the shaft by bringing its end right up into the generating station. The method adopted is to suspend the electric cable from a stranded wire rope carried on poles, suitable suspenders being used. In Fig. 1,141 an example is given of such a suspension of a 0·2 square inch three-core bitumen-insulated "Henley" cable, the details of the construction of which are given elsewhere. At the front of the picture the linear dimensions of the section shown are half the size of the actual cable.

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[*] *Journal of the Institution of Electrical Engineers*, Vol. LII., p. 198 (1914).

The suspenders used are of a patented type, manufactured by

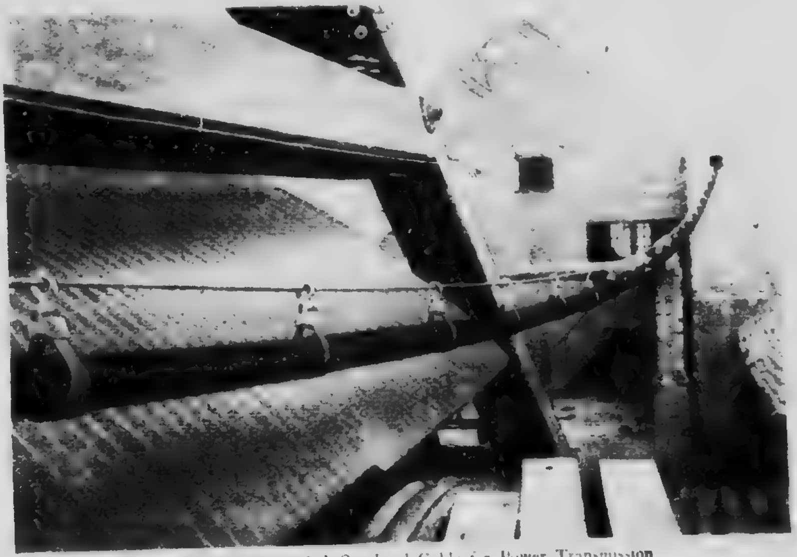

Fig. 1,141.—Suspended Overhead Cable for Power Transmission

Henley's Telegraph Works Company. The suspending steel rope consists of seven strands of No. 10 steel wire, each wire being 0·128 inch in diameter and having a breaking tension of not less than 2,500 lb. The suspending band is of untanned hide, well greased, with a steel rectangle secured by eyelets at one end and an eyeletted hole at the other through which the steel suspender passes; this suspender can be slipped on to the span cable at any point.

Various types of suspenders are used for both heavy and lighter cables under such circumstances as are referred to in the preceding paragraph. For instance, Fig. 1,142 is an illustration of a heavy type cable suspender manufactured by Messrs. W. T. Glover and Co. The sling is of sheet lead braided with waterproofed yarn, which offers prolonged resistance to adverse atmospheric influence and can be varied to suit local conditions. A wide base of support is provided for the cable, thus distributing the weight over a long bearing surface, and the ends of the slug are gripped between a rectangular collar and a wedge, both made of galvanised malleable steel. The wedge is supported by a hook which can readily slide along the span wire whilst the slings do not slip along the cable, but carry it forward as the hooks travel along on the wire.

A lighter type of suspender of similar construction, designed for light and medium weight cables and for cables slung underground in mines, is shown in Fig. 1,143. The sling in these cases is generally made of impregnated woven canvas, and a lighter hook of the pattern shown in Fig. 1,141 is used. This complies with a Home Office requirement for all cables in mines, to the effect that they must "be supported in such a manner as adequately to prevent danger and damage to the cables." The hook shown, whilst having an ample margin of strength for normal conditions, will open out if the cable be subjected to abnormal stresses such as may be caused, for instance, by the collapse of a roof; in such a case the cable will fall before it is damaged by being forcibly torn away.

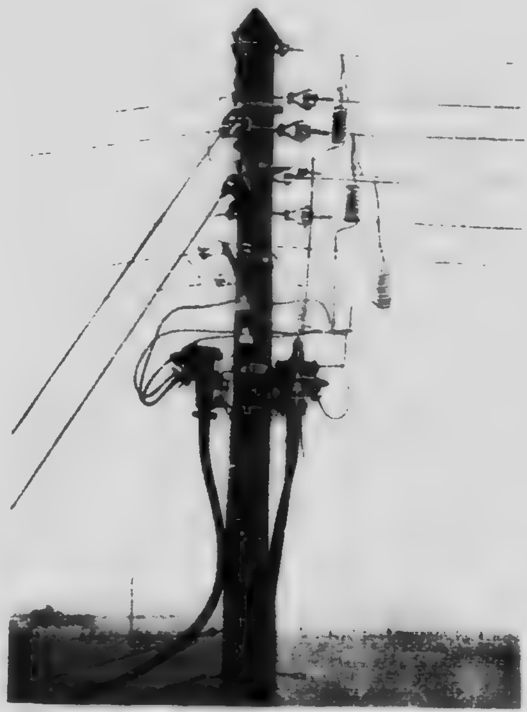

Fig. 1,142. Tapping Overhead Lines with Three-phase Cables.

The appearance of overhead cables suspended from wire ropes is familiar to the dwellers in many of our large towns, where, however, the suspended cable is more usually if not exclusively for telephonic and not for power transmission. That the power line, so suspended, does not differ very much in appearance from the multiple telephone cable will be evident from an inspection of Fig. 1,144, which is a view of a heavy cable erected by Messrs. Glover and Co. for conveying electric power to a mine, the position shown being a section of the cable carried overhead on a stranded wire catenary from the power-house to the pithead. A cheaper method would have been to convey the power, even for the short distance involved, by means of bare overhead wire, but this would have necessitated a cable-head at the top of the shaft for the joints between the cable and the open wires. Though more expensive, it is better practice to run the cable as shown right up to the switches, etc., in the power-house.

Junction with Open Wires.—Special contrivances are used where the cable whether aerial or underground, is connected to the open wires of an overhead system. If, as is frequently the case, the system of transmission is polyphase, the cable is terminated in a special fitting known as a cable-head, in which, careful attention being paid to insulation, its multiple conductors are separated and brought out, ready to be joined or "Tee-jointed" on to the bare overhead wires. One example of this for an underground cable has already been given in Fig. 1,131. Another is seen in Fig. 1,145, in which a 3,000-volt overhead transmission line is being tapped at a colliery pithead to feed the machinery for working the screens. Three trifurcating cable-heads can be clearly made out in the picture.

Fig. 1,146. Cable Suspended in Shaft [illegible]

Shaft Suspensions. There are certain special cases in which the conductor has to be suspended in a vertical position in which it comes under neither the "overhead" nor "underground" systems. These cases are those in which the conductor has to be carried down the vertical shaft of a mine, and as space does not permit of a detailed description of electric distribution in mines, a brief reference may be made to such cases here.

A portion of a cable in such a position is shown in Fig. 1,146. The cable at this point is partly supported by a cleat which rests upon supporting timbers as shown. A reference to the weights of cables given elsewhere will make it evident that the mechanical problem of supporting this dead weight for the full length of a deep shaft is a problem which must

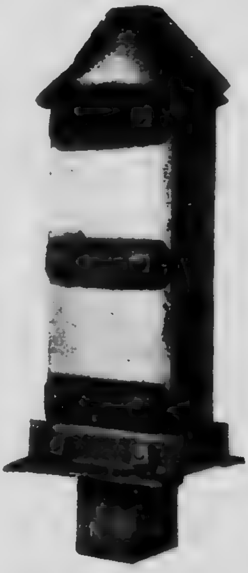

Fig. 1,147.—"Glover's" Cleat for Shaft Cables.

be carefully considered. Evidently specially designe supports must be provided at the top of th shaft where the cable enters, and these supports must be capable of carrying a heavy weigh reckoned in tons. The cleat shown in Fig. 1.146 i intended to assist the top suspension whilst als serving to keep the cable in its place. It is show on a larger scale, with additional fittings, in Fig. 1.147 The problem is to grip the cable firmly without injur to the outer or other covering. The cleat is made o two thick hardwood boards, about 30 inches long, the kind of wood used being selected to suit the conditions of the particular shaft. There are grooves on the inner sides of the boards into which the cable fits tightly and evenly when the halves of the cleat are clamped together as shown. With a firm grip of this kind, and with the cleat itself properly supported, each cleat can be safely relied upon to carry the weight of about half a ton of cable. In Fig. 1,147 the top of the cleat has been chamfered off and covered with a metal cap, which will fend off falling materials and the lodgment prevent of dirt and slime.

III.—EXTRA HIGH-VOLTAGE OVERHEAD TRANSMISSION

The advantages of increasing the voltage of transmission, to which reference has already been made (*see* pages 572 to 574, Vol. I.), have been so well realised that during the last few years systems using much higher voltages than any which were once considered possible have been erected in various parts of the world. Such voltages—say, 60,000 up to 150,000 volts—introduce into the problem new controlling factors which at much lower voltages were either non-existent or negligible, and some of these factors profoundly modify the design of the appliances used. The object of the engineers is to push the voltage up to the limit which can be used economically in view of the underlying laws and with the materials available. Postponing for a time the consideration of the limitations, which prevent an unrestricted raising of the voltage, we shall first describe some of the actual appliances in use, which are full of interest, and a knowledge of which will, later on, render the consideration of the limitations easier to follow.

Overhead Construction.—For reasons which by this time will be familiar to the reader, the transmission line for these high voltages is almost, if not quite, invariably a bare overhead conductor of copper or aluminium, carried on suitable supports, and insulated with special insulators at these supports. Both the supports and the insulators merit careful consideration

The Supports.—These usually take the form of steel or iron poles or towers of lattice-work type, designed with a view to economy of material whilst the necessary strength is obtained, the design also being affected by the position of the line and its exposure to special weather conditions. A simple form of such poles or masts is shown in Figs. 1,148 and 1,149, of which Fig. 1,149 is a side elevation and Fig. 1,148 an elevation looking along the line. The example is taken from an 80,000 volt line erected in South Africa from the Vereeniging station to the Rand, a distance of thirty-five miles. The transmission is three-phase at the voltage named, and there are four three-phase circuits, twelve conductors in all, carried on two parallel lines of masts. Each mast, therefore, carries six wires, the three for a single circuit being on one side of the mast, and the three for the other circuit on the other side. The three wires *a, b, c* for a single circuit are relatively to one another at the corners of an equilateral triangle, having one side vertical, two being suspended from the long upper cross-arm, and the third from the short lower cross-arm. The distance between the wires is 8 feet, and the lowest cross-arm is 31 feet 6 inches from the ground. The span is 500 feet, and the wires are stretched so that the greatest sag is 10 feet. Thus the lowest part of any conductor is not less than 24 feet 6 inches from the surface of the ground. As seen in Fig. 1,149, the mast is provided with a safety screen to prevent the possibility of men working on one circuit making contact with the circuit on the opposite side of the mast. The screen is a rectangular steel framework interlaced with galvanised steel-wire netting.

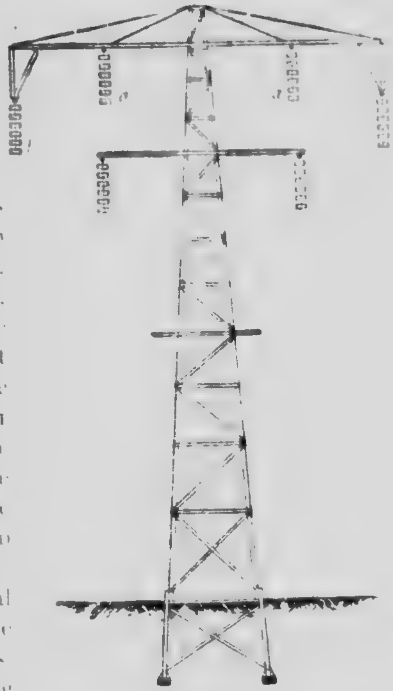

Fig. 1,148.

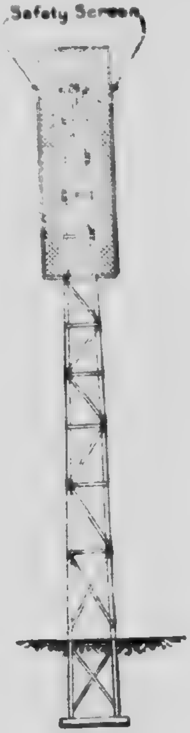

Fig. 1,149.

Double Circuit, Intermediate Mast, Triangularly spaced Conductors, Guard Wires and Screen.

Three other conductors are carried on the pole at the points *e e e*; these are earthed conductors intended to act as guard wires to protect the lines from lightning discharges, a subject to which reference will be made later.

The general appearance of the line is shown in Fig. 1,150, where the mast just described will be seen in the background. The masts in the foreground are of more elaborate construction, and are known as "anchor" masts. They are much stronger than the other or intermediate masts, and are designed to take the full strain of the conductors in the line direction, whilst the intermediate masts are intended to take the strain due to wind pressure transverse to the line. Every fourth mast is an anchor mast, and they are therefore 2,000 feet, or over a third of a mile, apart; their over-all height is 71 feet 6 inches, the lowest cross-arm being, as is the case with the lighter masts, 34 feet 6 inches from the ground. The cross-arms are nearly equal in length, and the conductors of each circuit are nearly vertically over one another and 9 feet apart. The three earthed guard wires are placed, as shown, below the live wire.

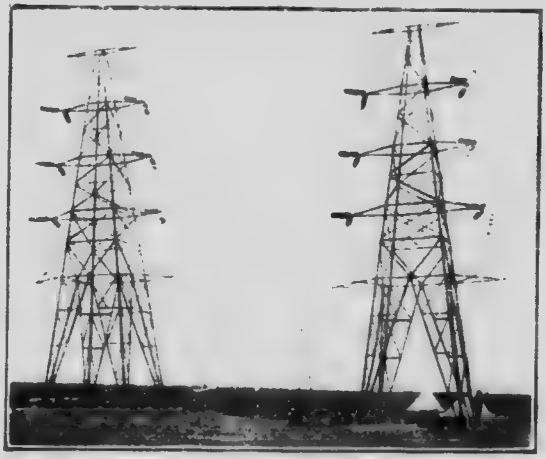
Fig. 1,150.—Duplicate [illegible] Lines [illegible] Volts in the Transvaal.

The running of four circuits as in the case just considered is a measure of precaution which is not often adopted, but double circuits are quite common, and single circuits are sometimes run. A standard steel tower for *double circuits* three-phase at 60,000 volts is shown by Fig. 1,151. The line is for the purpose of conveying power from Stave Falls, British Columbia, to the cities of Vancouver and New Westminster, a distance of about 35 miles. The three wires of each circuit are vertically over one another on either side of the tower, being carried by three cross-arms of open steel work. The wires are of stranded copper, with a hemp centre, and an earthed guard wire is carried on the apex of the tower.

Passing to a still higher voltage, an example of a standard *single-circuit* tower is given in Fig. 1,152. This is taken from the 110,000-volt transmission system of the Hydro-Electric Power Commission of the Province of Ontario, a Government corporation entrusted with the duty of distributing electrically some of the power of the Falls of Niagara to the rious municipalities of the populous province of Ontario. It has one f the most important transmission systems hitherto erected, there being ver 280 miles of 110,000 volt lines and 180 miles at lower voltages, 6,000 and 13,200 volts supplying energy to no fewer than twenty-nine municipalities at cost price. Its importance to the particular locality served will be realised when it is mentioned that there are no coal mines in Ontario.

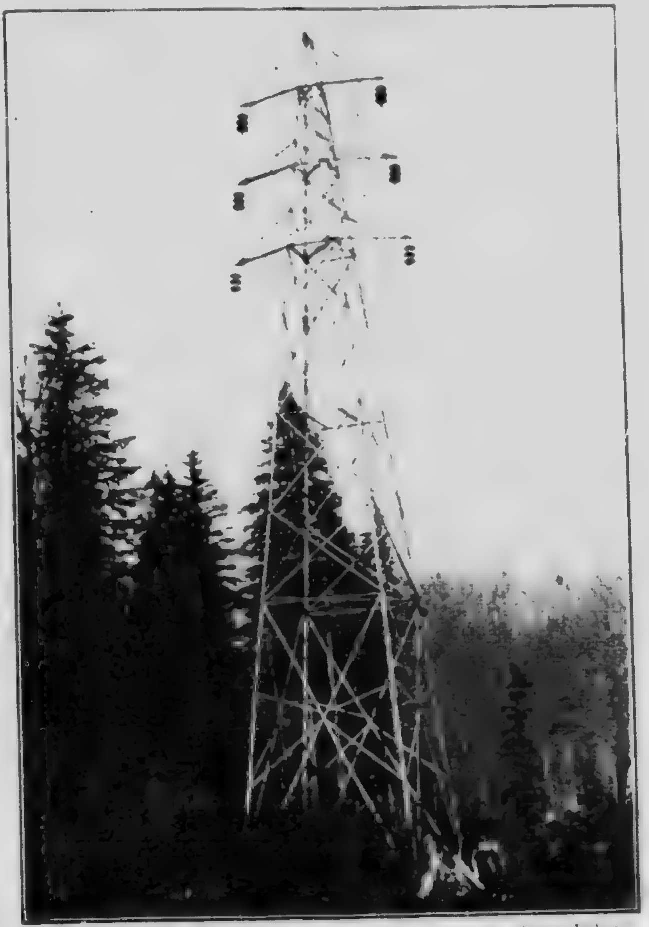

Fig. 1,151.—Double-circuit Tower, Vancouver. Conductors (60,000 Volts) Vertically Spaced. Earth Wire on Apex.

The tower shown in Fig. 1,152 differs somewhat in its design from those previously referred to, but the chief point to which attention is called is that the conductors are suspended from three projecting brackets at different levels, so placed that the conductors are at the corners of an equilateral triangle with one side vertical, as are the conductors in Fig. 1,148; with this difference, however, that the equilateral triangle in Fig. 1,148 is on one side of the support mast, whereas in Fig. 1,152 the mast is enclosed by the three wires. Later some particulars will be given of the method of erection of, and the footings provided for, these towers.

The triangular arrangement of the three wires of a circuit is maintained in this system, when double circuits are being carried by the same line

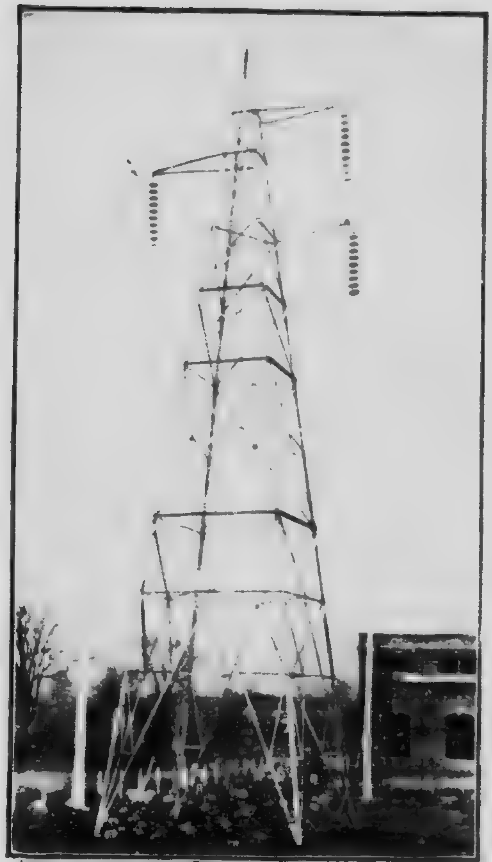

Fig. 1,152.—Standard Three-phase Single-circuit Tower, Ontario. Conductors (110,000 Volts) Triangularly Spaced.

of towers. An example i given in Fig. 1,153. whic shows a double circuit crossin a railway line. The tower are larger than the type show in Fig. 1,152, and the apex o the triangle is at the top, th base being horizontal. In th distance can be seen a tower o lighter construction carrying o the line under less exacting conditions.

The voltages in use have, however, been carried beyond the 110,000 volts of the Ontario scheme, for there was constructed in 1915 in California a transmission system designed to work at 150,000 volts, and to transmit 120,000 kilowatts from Big Creek in the Sierra Nevadas to Los Angeles, a line distance of 241 miles. For this transmission there are two steel tower lines, each carrying a single three-phase circuit with the conductors in a horizontal plane 17 feet 6 in. apart, the centres of the two lines being 80 feet apart. The appearance of these transmission lines and of the country through which they pass is shown on Fig. 1,154, whilst one of the standard

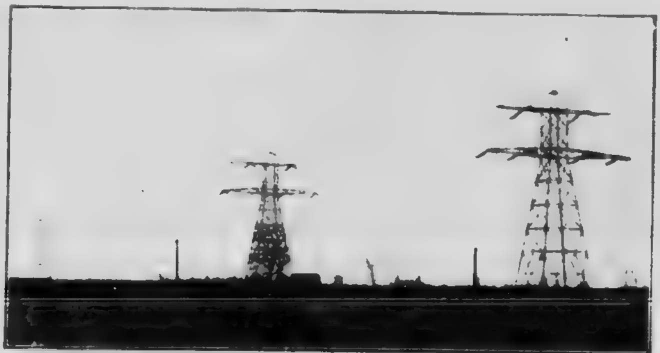

Fig. 1,153.—Typical Double-circuit Transmission Line, Ontario; Triangularly Spaced Three-phase Conductors.

wers is shown in Fig. 1.155. The towers are spaced [illegible] apart nd are 43 feet high from the ground to the cross-arms; the conductors e suspended as shown, and are sagged to give a minimum clearance 25 feet above the ground. The conductors are made of aluminium ving an outside diameter of 0·95 inch and a steel core consisting f seven strands of galvanised steel wire, each strand being [illegible] nch in diameter. They weigh 4,058 lb. per mile and are calculated o stand a maximum stress of 7,500 lb. A seven-strand galvanised Siemens-Martin steel cable is run on the tops of the towers as an earth re. Anchor towers are provided at intervals to safeguard the ngency of one or more of the conductors breaking. Special towers are o used at angles where the line is deflected.

Fig. 1.154.—150,000-volt Transmission Line in California.

It will be gathered from the foregoing that the type of tower to be adopted depends on the number of circuits to be carried, the character of the country through which the line has to pass, and the climate; also on the type of insulator. The towers so far illustrated have all been four legged, but three-legged towers have also been designed and erected, but this method has not been so widely adopted as the other. One of these three-legged towers is shown in Fig. 1.156.* It is used to carry the 140,000 volt single-circuit line of the Eastern Michigan Power Company.

Attention has been directed from time to time in the foregoing to the relative positions of the three conductors which form a single circuit, and it will have been noticed that the practice is far from uniform. The distance apart of the separate conductors depends, of course, upon the voltage, but their relative position is decided by other considerations. For instanc although examples to the contrary have been given, it is not now considered good practice to place two or more conductors in a vertical plan especially where snow and ice are likely to collect on the wires and suspension insulators are employed. It has been observed that ice tend to collect more at the centres of the spans than near the towers, and thi should be take into consideration.

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* From the *General Electric Review*, June 1912.

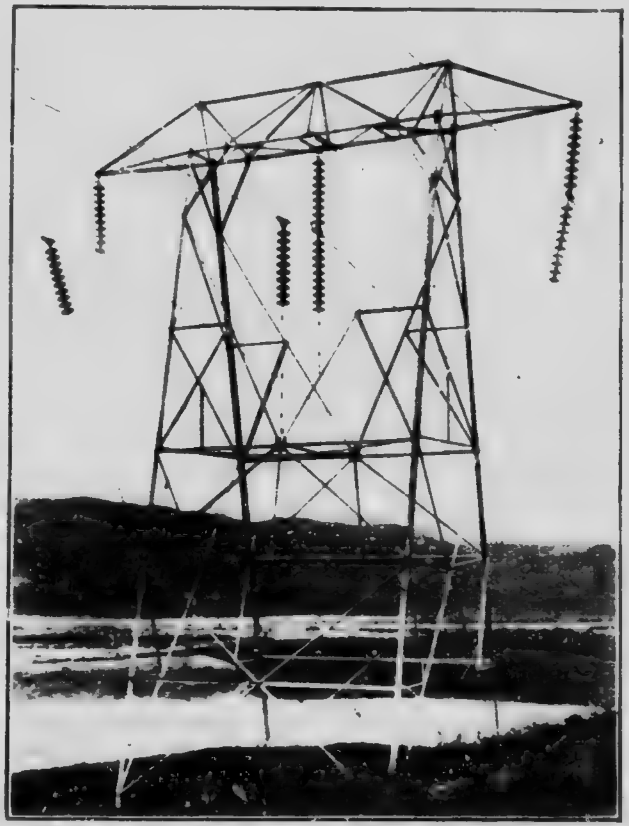


Fig. 1,155.—Single-circuit, 150,000 volts, Standard Tower; Conductors Horizontally Spaced and Anchored.

Foundation and Erections. It is obviously a matter of great importance that the towers described should be erected on secur foundations, which should be all equally stable for the different legs of the tower. The method adopted for the standard towers (Fig. 1.152) of the Ontario transmission system is shown in Fig. 1.157. A riveted steel grillage 28 inches square is buried about 7 feet deep in the soil on a foundation of field stones, and is bolted to a leg angle about 8 feet long and projecting 12 inches to 15 inches above the surface of the ground. Other details are given in the figure. These standard grillages and leg angles weigh 600 lb., whilst in poor ground, where heavier construction may be required, the weight may run up to 1,830 lb. For corner towers with large angles and long spans, or in still poorer positions, concrete footings are used, as shown in Fig. 1,158; dimensions of the details are given.

The usual method of erecting such wers is to deliver the separate parts the spot and to build up the tower ing on the ground. It is then tilted to its place, as shown in Fig. 1,159. As during the tilting faults may develop, is very necessary that after erection he structure should be carefully inpected to ascertain whether any of he members have been distorted and hether any of the bolts require to be ghtened up.

The above methods of designing the undations and erecting the towers are ketched from a particular system to show he necessity for careful design in this ortion of the work. It would obviously carry us too far afield to pursue this aspect of the subject farther

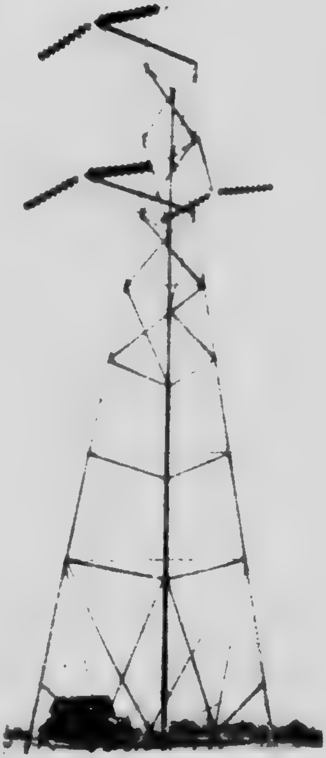


Fig. 1,156.—Three legged Standard Tower for 14,000 Volts Transmission

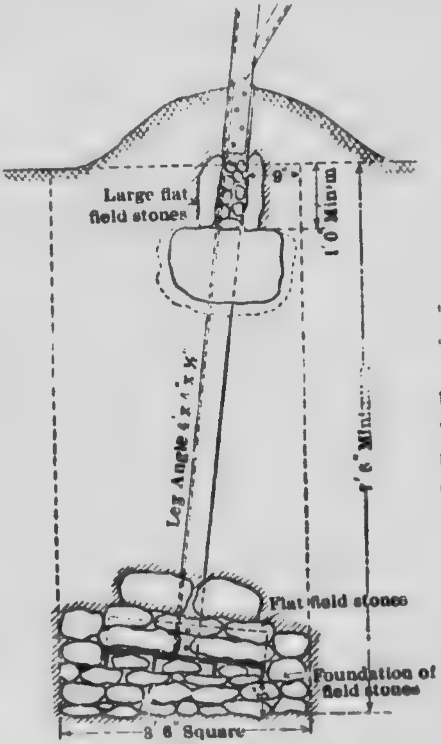


Fig. 1,157.—Setting of the Footings of a Standard Tower

Extra High-voltage Insulators.—The very high voltages which we have just been considering, require for the effective insulation of the conductor insulators fundamentally different from the ordinary petticoat insulators supported by a steel central pin which are universally employed for overhead work in telegraphy and telephony, and have also been found serviceable in many power transmission schemes at low and moderately high voltages. It is true that a good porcelain

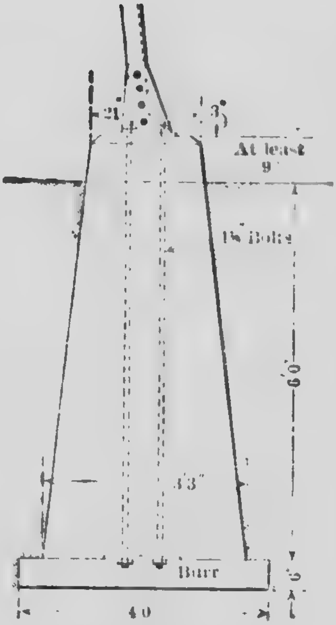


Fig. 1,158.—Setting of the Footings of a High or Special Tower

double-shed insulator, such as is depict in Fig. 1,137, may safely be employed f voltages up to 12,000 volts, or ev higher, and, by increasing the size an modifying the design, single insulators this general type may be employed much higher voltages. Beyond a certa voltage, say 60,000 to 70,000 volts, the whol question of the fundamental design of th insulators has to be reconsidered. A compared with suspension insulators de scribed below, the central pin supported insulators, referred to above, are, for highe voltages, much more costly and weaker, both electrically and mechanically. Some instances of the modifications of the pin-supported insulator to enable it to carry high-voltage lines, have already been given on pages 1110 and 1111. The description of a few further modifications will be a convenient introduction to the consideration of the more modern type of "suspension" insulator.

It will be noticed that the material of the insulators shown in Figs. 1,137 to 1,140, and in the telegraph section, is all in one piece. The difficulty of manufacturing such insulators without any microscopic faults developing in the firing increases rapidly with the size, and, to minimise this danger, a further development is to construct the insulator in two or more parts, which are then cemented together. This overcomes the manufacturing difficulty and the size can be further increased

Fig. 1,1[illegible].—Erecting Towers in Ontario until a limit is reached from the other considerations, mechanical and electrical, referred to above.

Two examples of such compound insulators will suffice. In Figs. 1,160 and 1,161 there is shown a two-piece insulator, consisting of one double-shed insulator cemented inside another. The upper insulator has a bell 10½ inches in diameter, but is only 2¾ inches in vertical height, whilst the inner insulator has a bell 7½ inches in diameter with an inner shed 3½ inches in diameter, and a vertical height of about 5½

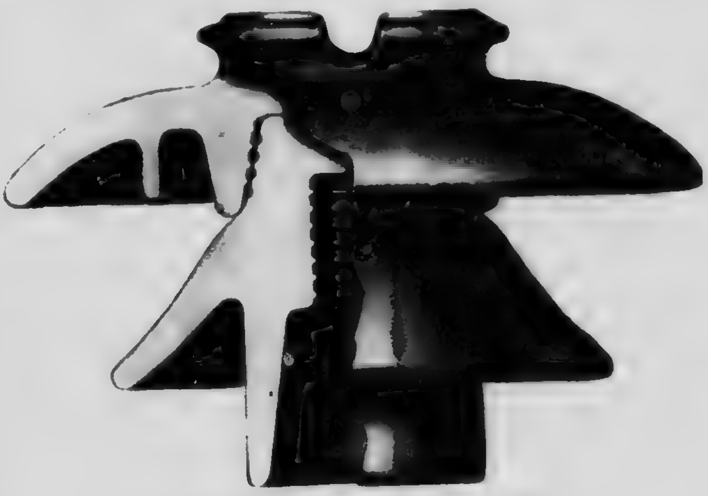
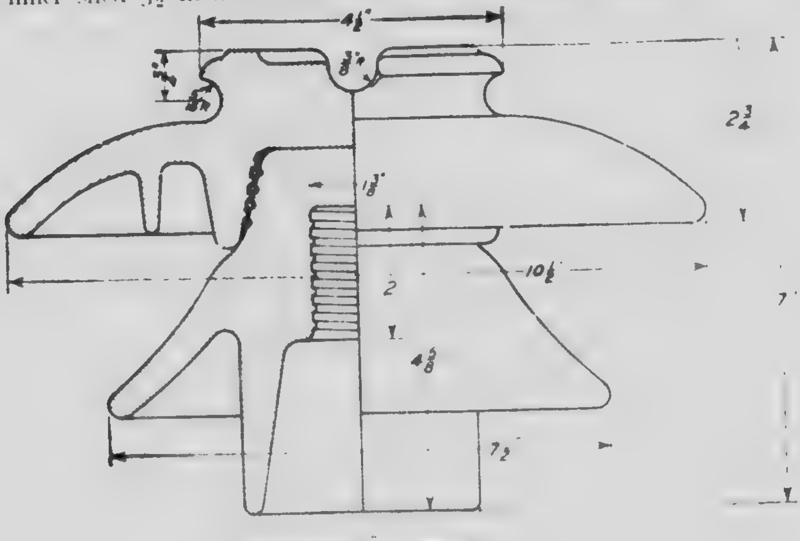


Fig. 1,160.—Multi-shed Porcelain Insulator for [illegible]



[illegible]

inches. The over-all height of the insulator is 7 inches. The insulat is intended to work up to a line voltage of 45,000 volts, and is test up to 145,000. Its weight is 11 lb. Were the attempt made manufacture in a single piece, in quantity, an insulator of this size an

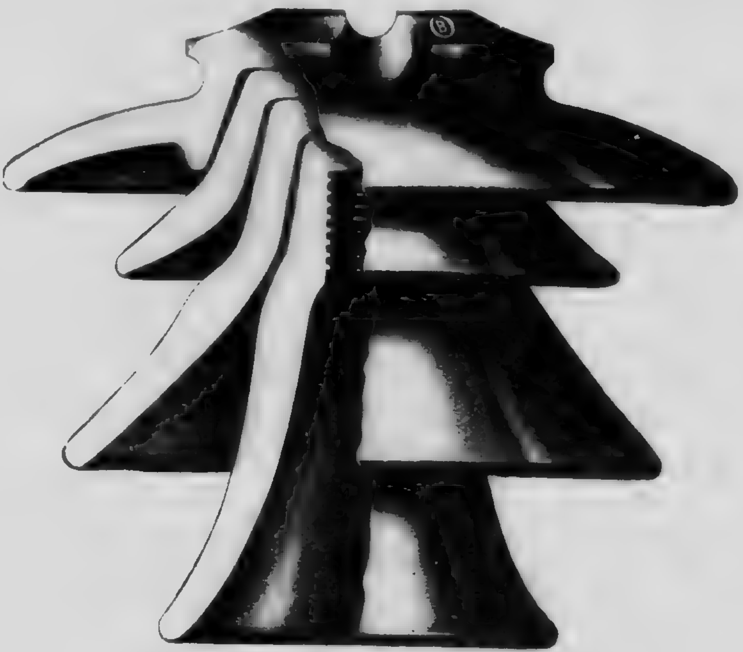


Fig. 1,162.—Multi-shed Porcelain Insulator for 70,000 Volts.

shape, the firing process would be difficult, and many faulty insulators would be produced, thus raising the average cost.

A further example of this type of insulator is given in Figs. 1,162 and 1,163, which, it will be found, depict a compound insulator built up of no fewer than four single-shed insulators cemented one inside the other. The dimensions of the separate insulators are given in Fig. 1,163, and it will be noticed that, except as regards No. 2, from the top the bells become narrower and the insulators taller as we proceed from the outside to the inside. It is obvious that the outer surfaces of the inner bells are not so effectively screened from rain as in previous examples. The overall dimensions are 14 inches wide by 12 inches high, and the insulator is intended for a line voltage of 70,000 volts; it is tested up to 175,000 volts at the works.

A little consideration of these examples will show that we are rapidly approaching the limits of this general type of insulator if only from the echanical point of view. This conclusion, with others, is brought out the following table:

TABLE XV.—PARTICULARS OF SOME HIGH-VOLTAGE [illegible] INSULATORS

Type	[illegible]	Width × Height	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]	[illegible]	[illegible]	
ble-shed (ordinary)		3¼ × 3	1·2	5¼	1¼	6,000
Do.	1,137	4¼ × 4½	1·67	7½	1¼	11,000
-shed	1,139	[illegible] × 3¾	1·75	8	1	[illegible]
-shed (compound)	1,160	10½ × 7	11·0	21¼	7	[illegible]
-shed (compound)	1,162	14 × 12	33·0	40½	10	70,000

It will be seen that, except for the first item, where the allowance is robably excessive, the length of the leakage path is approximately pro

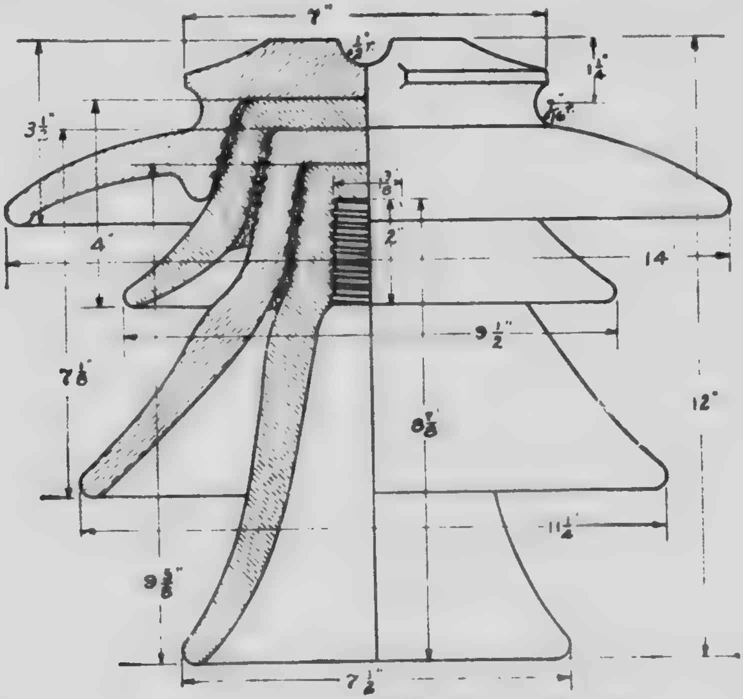


Fig. 1,162.—Dimensions of Multi-shed Insulator for [illegible]

portional to the maximum line voltage, but that the weight is increasing much more rapidly. Thus, whilst the line voltages increased from 11,000 to 70,000, or about 6·4 times, the weight per insulator has increased from 1·67 lb. to 33 lb., or about 20 times. It is obvious that the limit in this direction has been reached if not overpassed, for a single insulator weighing 3[illegible] lb. is something of a monstrosity. Moreover the difficulty of manufacture and the cost are increasing in much the same ratio as the weight.

A further examination of the table will show that another electric condition is beginning to emerge, namely, the possibility of the P.D. between the line and the steel bolt supporting the insulator breaking down the intervening air, which is an interposed, and parallel, dielectric, thus leading to arcing or "flashing over" between the two. The question of the sparking voltages at different distances in dry air has been dealt with in Vol. I. (*see* pages [illegible] to 132). The experiments detailed there were made under carefully defined laboratory conditions. In practical problems, such as we are now considering, the conditions are much more complex. Thus the humidity, pressure and temperature of the air are all of importance besides the shape and position of the opposed electrodes. Atmospheric electricity also plays its part, and if protective devices fail may start an arc which, as remarked elsewhere, can then be maintained by a much lower voltage than is necessary to start it. The curves already given (*loc. cit.*) show that to prevent arcing the distance of the opposed surfaces must be increased more than the voltage, a condition which is not satisfied by the figures given in the table. The distances given there are measured in one or more steps from the lip (assumed "wet") of the outermost bell to the uninsulated steel bolt, for in wet weather the

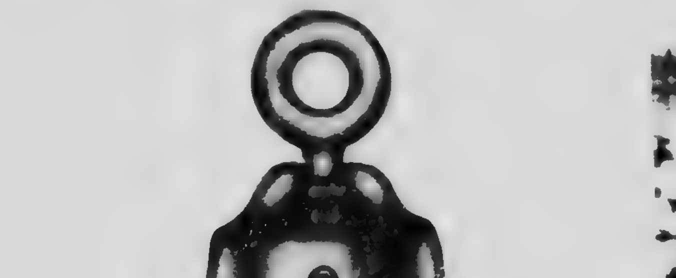
Fig. [illegible].—Seven "Suspension" Porcelain Insulators Tested at [illegible] Volts.

whole of the wet surface of this bell is at line potential. We shall give some actual curves later (see pages 1135 and 1136) when dealing with other effect

Suspension Insulators. These and other considerations have led to the abandonment of what is sometimes called the "pin" type of insulator, and the substitution for it of the "suspension" type. In the latter, instead of one large insulator a number of small porcelain insulators are strung *in series* between the line wire and the support, as shown in the illustrations of these supports already given. A series of seven such units is shown on a larger scale in Fig. 1,104, supporting a stranded line wire [illegible] flashing over under test at 375,000 volts.

[illegible]

An exam[illegible] of a suspen[illegible] insulat[illegible] this type in actual use [illegible] given on [illegible] 1,105 where [illegible] [illegible] lines of the [illegible] Power Company. The conductors shown [illegible]



[illegible] Met[illegible]

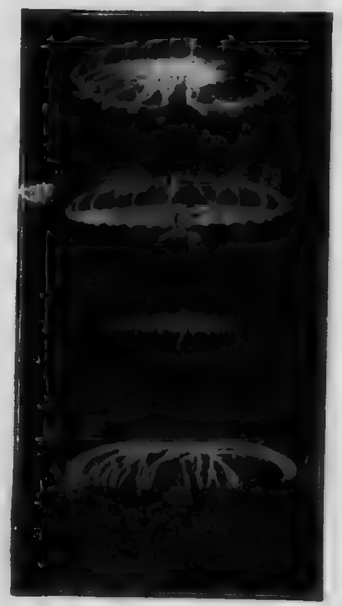


Fig. 1,167.—Discharges Spreading Over Insulators

clamped to the lowermost insulator, is intended to work at 140,000 volts, the pressure used by this Company in 1912.

Further details of suspension insulators as manufactured by the Ohio Brass Company are given in Fig. 1,166, which shows two units of their "Type B" insulator, the lower unit being shown in section. Each unit consists of a porcelain disc D D, of the shape shown, having a central projecting hub and with concentric rings on the under surface; it is in effect a shallow quadruple-shed insulator of a special shape. The central hub is cemented into a malleable iron cap C, which, at the [illegible] carries the socket of a ball-and-socket joint. In the central hole below the porcelain, there is cemented a forged steel centre pin P, which, at its lower end, terminates in the ball which is to work in the socket of the insulator next below. The suspension device is simple, and gives a fairly flexible chain of insulators which can be extended or shortened as the conditions may require. Each disc is 10 inches in diameter, and the length of the chain is 5 inches per insulator, with proper allowances for the eye-bolt and the suspension fitment. Thus the flash in Fig. 1,160 is seen to be about 33 inches long if it be this pattern of insulator which is being used.

It will be noticed that the flashes between the support and the wire in Fig. 1,164 are clear of all the insulators except the top one. This is due to the horns projecting from the clamps of the suspended conductor. When such

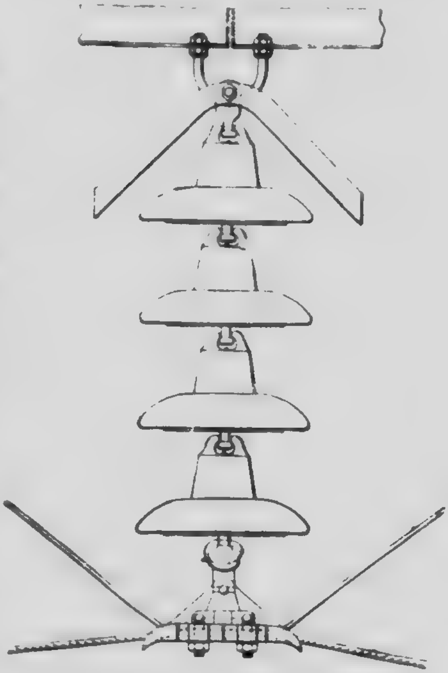


Fig. 1,168.—String of Insulators with Arcing-horns.

horns are not used the arc will be found jumping from insulator to insulator or spreading over the surface of the porcelain, as shown in Fig. 1,167. Under these conditions the insulators deteriorate more rapidly. Still more complete protection of the individual insulators is obtained if arcing horns or rods are provided both top and bottom, as shown in Fig. 1,168. Because of the concentration of the electrostatic field at the tips, such arcing rod will cause the flash-over to occur at a lower voltage than the unprotected chain would stand, but the practical advantages are held to counterbalance this disadvantage.

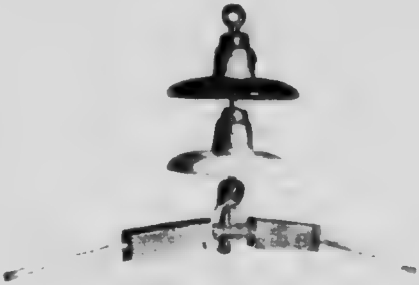


Fig. 1,169.—Details of Clamping the Conductor to Lowermost Insulator.

Attachment of Conductor.—Methods for clamping the conductor to the lowermost insulator of a suspension string may be noticed in passing. Some examples will be seen in preceding illustrations (*see* Figs. 1,164, 1,165 and 1,168), and details of an additional example are given in Fig. 1,169, in which it will be noted that the clamping arrangements are carefully designed, so that whilst gripping the wire tightly they do not [illegible] or cut it in any way. This is obviously very important.

In some cases the string of insulators has to take a horizontal instead of a vertical dead-weight strain. This happens when the tower is at the end of the line (*see* Fig. 1,153), and also [illegible] less when it is necessary to anchor the line to prevent dangerous swaying in the wind. A strain insulator clamp for, say, the conductor at an end tower is shown in Fig. 1,170, where it will be noticed that the wire is gripped for a considerable distance between two plates with moulded half grooves encircling the wire, and giving a firm, non-denting grip. For such cases strong special insulators are sometimes employed, but considerations of space preclude us from carrying this part of the subject farther.

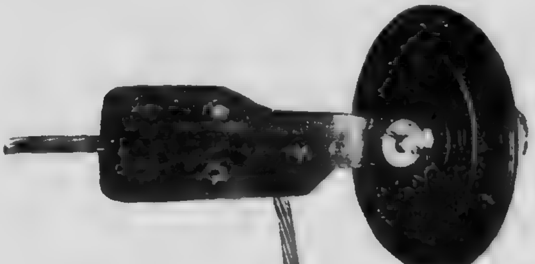


Fig. 1,170.—Details of Clamping the Conductor to a Strain-terminal and horizontal String of Insulators.

Flashing-over.—Other interesting problems are involved in the *flashing-over* of a string of insulators, such as is now being considered. Thus, it can be shown from elementary principles that the voltage at which a string of n units will flash over is necessarily lower than n times the voltage at which one insulator will flash over, the insulators, of course being of identically the same pattern. This is due to the fact (i.) that the insulators form a line of equi-capacity condensers in series between line and earth; (ii.) that the eye-bolt metal of each insulator has also an electrostatic capacity to earth; and (iii.) that the voltage applied to the line is an alternating and not a steady voltage. As shown elsewhere (see Vol. I., page 798), the charging current for a condenser of capacity K is

$$c = 2\pi f K (V_1 - V_2),$$

where f is the frequency and $V_1 - V_2$ the R.M.S. value of the alternate voltage applied. From this it is apparent that when n and K are fixed the value of $(V_1 - V_2)$ will vary with c. Now an insulator near the line has to carry not only its own charging current, but also that of all the other insulators between it and earth, and therefore, even though its capacity K be the same as that of other insulators, the voltage across its dielectric will be higher than that of an insulator lower down the chain. The voltage is therefore unequally distributed along the chain, and the insulator nearest the line is subjected to a greater voltage stress than those nearer the earth, and will therefore flash over sooner, with the consequence that the whole chain breaks down.

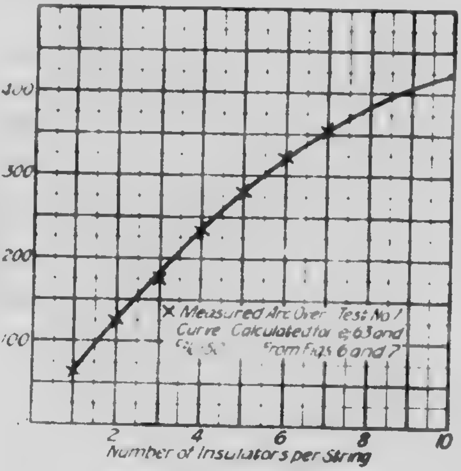


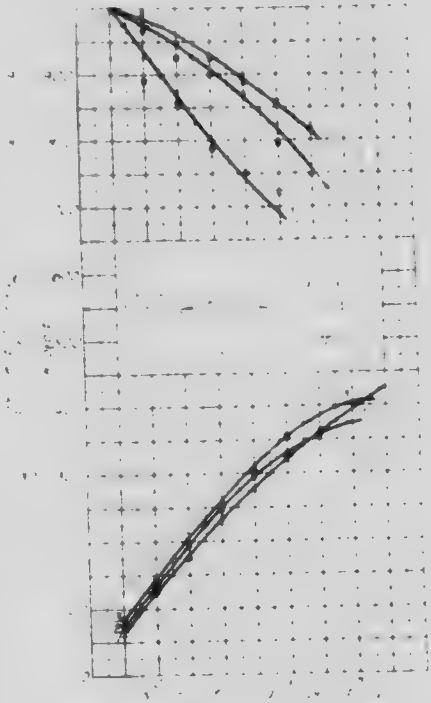
Fig. 1.171.—Connection between the Flashing-over Voltage and the Number of Insulators Strung Together.

The mathematical calculation of the distribution of voltage on the string of insulators is fairly simple if a reasonable assumption be made as to the ratio of the two capacities referred to above, *i.e.* the capacity of the insulator and the capacity of the eye-bolt. On the assumption that this ratio in a given case was 50:1, the curve in Fig. 1.171 gives the result of the calculation for strings of insulators consisting of from 1 to 10 elements, and the crosses give the actual values of the flashing-over voltage as determined by experiment. The curve is one of several on this subject published by Mr. F. W. Peek, Junior, of the General Electric Company of Schenectady, in the *General Electric Review*. It will be noticed that a single insulator of the set flashed over at 63,000 volts but that a string of seven flashed over at 350,000 volts, which is [illegible]ch less than 63,000 [illegible] 7 [illegible] The theoretical curve shows that [illegible] tring of ten units would have flashed over at about [illegible] volts. The [illegible]seness of the agreement between calculation and experiment indicates [illegible]at the assumption made for the ratio of capacities was fairly good.

The influence of the shape of the insulator on the flash-over voltage [illegible] by Mr. Peek in Fig. 1.172 from actual tests. The shapes of the units [illegible] are shown inset in the diagram and it will be noticed that the flash[illegible] voltage for a single insulator is approximately [illegible]5 kilovolts for No. 1, [illegible] kilovolts for No. 2 and 85 kilovolts for No. 3. When, however, a sufficient number is strung together [illegible] string of 8 units of No. 1 is found to stand a higher voltage than a similar string of No. 2 and that [illegible] 9 units No. 1 stands highest of [illegible] This change of the relative [illegible]sition is due to the better design [illegible] No. 1 for string balance.

At the top of the diagram [illegible] 1.172 are three other curves [illegible] what is called the "string efficiency," which is defined as

String efficiency
flash-over voltage of [illegible]
the flash-over voltage of [illegible] n



[illegible]

The curves show the calculated, and the plotted points the test, efficiencies. The agreement is best for No. 2; all the curves, however, are unreliable for a string of 2 units, but fairly reliable for 3 or more units. This might be expected from the assumptions made for the calculation, as the correctness of these assumptions affect short strings more than long strings. It is interesting to note that for a string of 6 No. 3 type has an efficiency below 70 per cent, whilst the efficiency of No. 1 for 7 units is about 82 per cent.

From the design of the insulators it would be expected that driving rain would increase the tendency to flash over, and experiment confirms this view. The results are shown in Fig. 1.173. For a single unit the rain lowers the flash-over voltage from 75 to less than 50 kilovolts; for 5 units the drop is from 275 to 200 kilovolts. Extrapolation would seem to indicate that the curves would cross at about 9 units, but the

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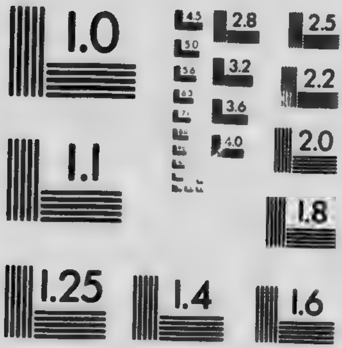

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experiments were not carried beyond 6 units. A string efficiency curve is also given.

High-voltage "Corona" Discharges.—The difficulties of insulation at the supports and the losses consequent upon these difficulties not being completely overcome are not the only points which differentiate the conditions of working at extra high voltages from those obtaining at lower though still high voltages of, say, 40,000 volts and under. The most important of the new data, next to insulation at the supports, are the losses introduced by what is now known as the "corona" phenomenon, which is only our old friend the "brush, or glow, discharge," which has been known to experimenters in electrosatics from quite early days, and is now of importance to engineers because of the energy losses involved. References will be found to it in Vol. I., at pages 82, 131, 701, and elsewhere, which are worth re-reading in this connection.

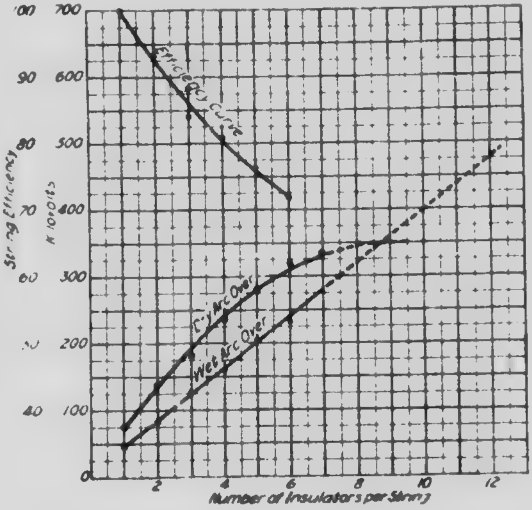

Fig. 1,173.—Effect of Rain on Flashing-over Voltage.

For our present purpose the "corona" effect may be briefly described as follows. If two parallel and insulated wires be suspended near one another in dry air and connected respectively to the terminals of a source from which high-voltage alternate currents can be obtained then, as the voltage is gradually raised, and long before the sparks pass which are referred to on pages 129 *et seq.* of Vol. I., the wires become luminous in the dark, and the luminosity increases in brightness and spreads out farther from the wires until sparks begin to pass. The passage of the sparks is indicative of the breaking down or smashing of the dielectric and the passage of a current of electricity, but the above-mentioned earlier effects also indicate a discharge current due to the ionisation and repulsion of the air particles in the neighbourhood of the wire.

The phenomena were investigated from an engineering standpoint by Mr. C. F. Scott as early as 1898[*] in some experiments which he made at East Pittsburg on lines a little over 1,000 feet long, carried on insulators, and some very interesting results were obtained. During the last few years, owing to the high-voltage transmissions we are now considering, the subject has attracted a great deal of attention, and numerous experiments have been made, both in the laboratory and on actual transmission lines, confirming and extending Mr. Scott's results. The facts ascertained are both important and complex, and will now be briefly described.

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[*] See *Journal of the American Institution of Electrical Engineers*, Vol. XV., 1898.

The most important information required by the engineer is the voltages at which the corona losses begin to be of engineering importance under the various conditions obtaining in practice, together with data regarding the actual losses at these and higher voltages. The results of numerous experiments are given in curves similar to those shown in Fig. 1,174, in which the pressures used for the tests are plotted horizontally, and the losses in kilowatts per kilometre are plotted vertically. The four curves are for four different distances apart of the wires, namely, 50, 100, 125, and 175 cms. respectively. The curves are all of the same general type, and show that at low voltages the losses are inappreciable, at higher voltages they rise somewhat slowly with the increase of voltage, but that after a certain voltage has been passed the losses rise very rapidly indeed for further increases of voltage. Thus on the 50 cms. (20 in.) curve the loss is practically inappreciable below 60,000 volts; from 60,000 to 90,000 volts pressure it rises somewhat slowly up to 1 kilowatt per kilometre, and beyond 90,000 volts the rise becomes very rapid, so much so that between 100,000 and 110,000 volts it increases from 4·2 to 8·0 kilowatts per kilometre, and reaches 18 kilowatts at 130,000 volts. The other curves are similar, the difference being that the pressures marking the three stages are higher.

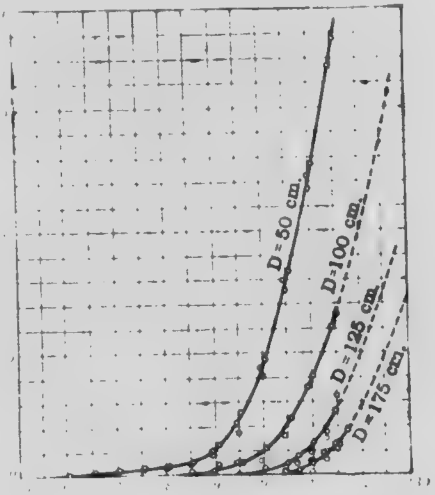

Fig. 1,174.—"Corona" Losses of Strand-Overhead Cables at Different Distances

The effect of increase of distance, however, is not very marked. Thus a loss of 5 kilowatts per kilometre is reached at 102,000 volts with the wires 50 cms. apart, whereas if the distance be doubled the same loss occurs at 114,000 volts, an increase of only 12 per cent.

The above experiments were made with seven-strand cables of 42 sq. mm. sectional area, the voltage frequency being 50 ∿, and the results have been reduced to a standard barometric pressure of 750 mm. and a standard temperature of 17° C. These conditions should be noted, for experiments were not carried beyond 6 units. A string efficiency curve is also given.

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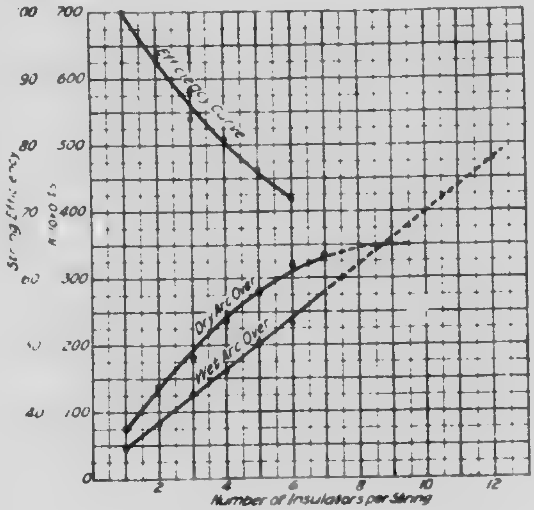

Fig. 1,173.—Effect of Rain on Flashing-over Voltage

For our present purpose the "corona" effect may be briefly described as follows. If two parallel and insulated wires be suspended near one another in dry air and connected respectively to the terminals of a source from which high-voltage alternate currents can be obtained then, as the voltage is gradually raised, and long before the sparks pass which are referred to on pages 120 *et seq.* of Vol. I., the wires become luminous in the dark, and the luminosity increases in brightness and spreads out farther from the wires until sparks begin to pass. The passage of the sparks is indicative of the breaking down or smashing of the dielectric and the passage of a current of electricity, but the above-mentioned earlier effects also indicate a discharge current due to the ionisation and repulsion of the air particles in the neighbourhood of the wire.

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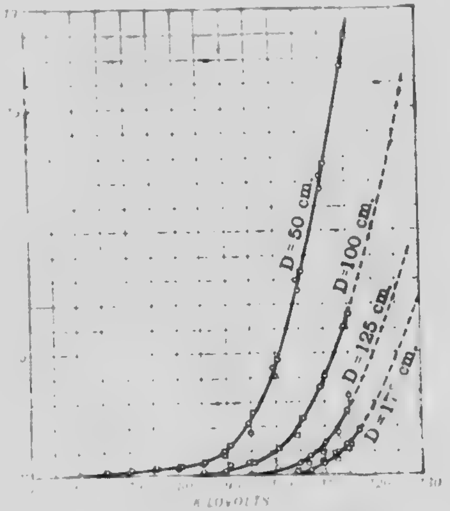

Fig. 1,174.—Corona Losses of Seven-strand Overhead Cables at Different Distances.

The effect of increase of distance, however, is not very marked. Thus a loss of 5 kilowatts per kilometre is reached at 102,000 volts with the wires 50 cms. apart, whereas if the distance be doubled the same loss occurs at 114,000 volts, an increase of only 12 per cent.

The above experiments were made with seven-strand cable of 42 sq. mm. sectional area, the voltage frequency being 50 ∿, and the results have been reduced to a standard barometric pressure of 750 mm. and a standard temperature of 17° C. These conditions should be noted, for a variation in any one of them will alter the corona losses, as we shall see presently.

It will be, however, interesting first to compare the above experiments made in the laboratory with results obtained from tests on an actual transmission line as given in Fig. 1,175, in which the marked points give the corona losses as measured by experiments on a line 63·5 miles long supplied with three-phase currents. The line was at a high altitude in the mountains, as evidenced by the barometric pressure, which was only 23·8 inches; the wires were each 0·375 inch in diameter and were spaced triangularly 124 inches (over 10 feet) apart; the temperature when the experiments were made was 51° F.

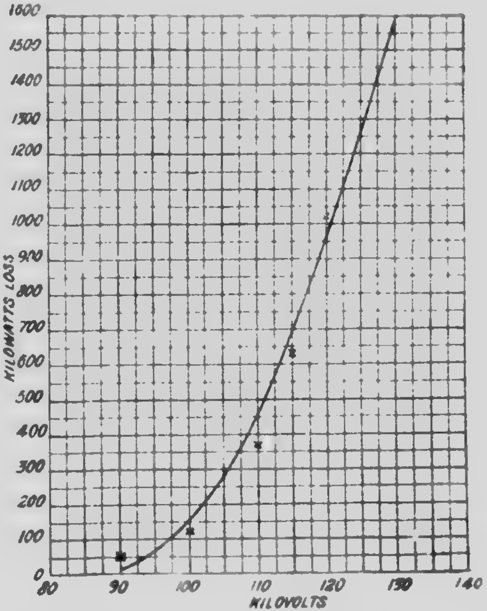

Fig. 1,175.—Corona Losses on a 63·5-mile Line at Various Pressures.

The smooth curve in Fig. 1,175 is calculated from a formula worked out by Mr. F. W. Peek, Junior, as embodying the results of numerous experiments, in which the attempt is made to allow for the variation of the chief conditions which experiment has shown to influence the corona losses, and the agreement of the curve with the experimental points is a test of the degree of accuracy of the formula. As this agreement is fairly good, it will be interesting to give the formula, which is as follows

$$P = \frac{344}{\Delta} f \sqrt{\frac{r}{s}} (\quad)^2 10^{-5} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P = power lost in kilowatts per kilometre,

$\Delta = \frac{3{\cdot}926\, b}{273 + t}$

b = barometric pressure in inches of mercury

t = temperature in °C.,

f = frequency in cycles per second,

r = radius of wire in cms.,

s = distance apart of wires in cms.,

applied sine-wave voltage to neutral in kilowatts,

critical disruptive voltage to neutral in kilovolts.

The voltages between lines will be obtained by multiplying by 1·73 for three-phase voltages and by 2 for two-phase. The power loss given by the equation is for fair-weather conditions. The loss during storms is higher, and can be approximately found by taking e_v as 0·8 of the e_v for fair-weather conditions.

The influence of periodicity is separately shown in the two curves of Fig. 1,176, one of these curves being for a periodicity of 50 and the other for 43 cycles per second. In this diagram, also, as in the last one, the smooth curve is calculated from the above formula, and the results of experiments are shown by the plotted points. Here, again, the agreement is fairly close, but not quite so marked as in Fig. 1,175. The influence of periodicity at very high voltages is very marked. Thus at 100,000 volts theory shows an increase from 18·1 to 24·0 kilowatts per mile in the corona loss, whilst the experiments at this particular voltage give the increase as from 17·0, to 25·7 kilowatts for a change of periodicity in each case from 43 to 50 cycles per second. The tests were made with single-phase currents between two wires 0·064 inch in diameter and 48 inches apart.

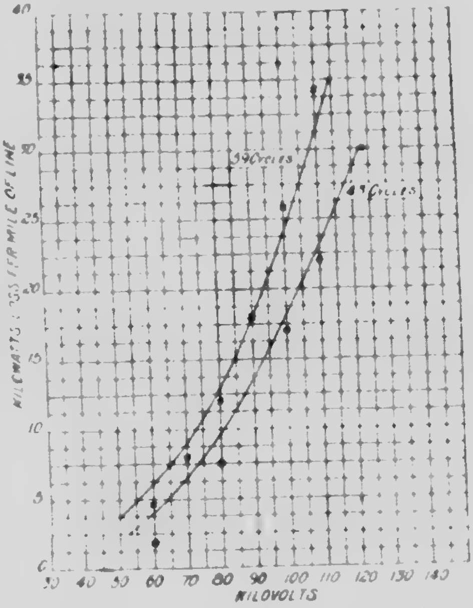

Fig. 1,176.—Influence of Periodicity, etc.

The effect of some of the other variables on what is specified as the "beginning of corona voltage" is shown in Fig. 1,177. The phrase is used to denote the first faint appearance of a corona effect in the dark, and though apparently somewhat vague, the curves are strictly comparable with one another, and are very interesting. The abscissæ or horizontal ordinates are the diameters of the conductors in inches from 0·225 to 0·8 inch. The curves sloping upward to the right show how the increase of the critical voltage rises with the increase in the diameter of the wire which involves the diminution of the curvature, a factor which, as we have shown elsewhere (*see* Vol. I., page 131), is a predominating one in the electric stress in the dielectric in the neighbourhood of a charged conductor, and therefore bears materially on the questions connected with the failure or breaking down of the dielectric. From this point of view, it would have been interesting to have had the curves carried down to smaller diameters, as the stress on the dielectric rises rapidly below about half the lowest diameter shown in the table. This is shown in Fig. 1.178, which, in kilovolts per centimetre, gives the electric stress near the conductor at which the air breaks down and the corona becomes visible. This curve shows how rapidly the stress rises as the wire becomes smaller, and also shows that the dielectric air is *apparently* stronger in the neighbourhood of fine wires than near larger ones. Considerations of space forbid us to carry this very interesting part of the subject farther.

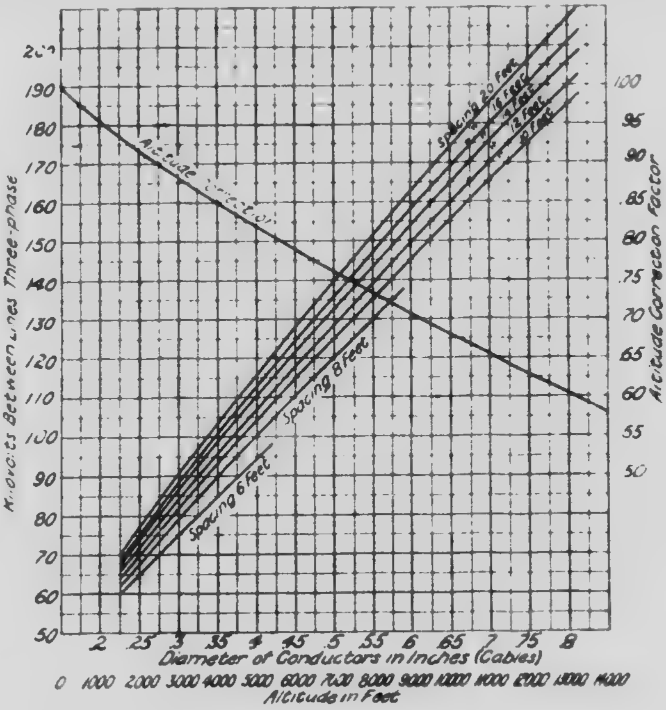

Fig. 1.177.—Curves showing the Pressure at which Corona Losses begin for Different Wires, Spacings and Altitudes.

Returning to Fig. 1.177, the single curve crossing the others is the altitude correction curve, its scale of abscissæ being marked below the diameters, and its scale of ordinates, from 1·00 downwards, on the right-hand side. This curve, for any specified altitude, gives a reducing correcting factor, by which the voltages in the left-hand scale must be reduced to

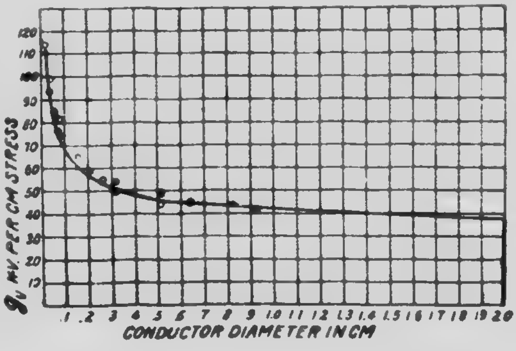

Fig. 1.178.—Conductor Diameters and Dielectric Stress.

obtain the voltage at which visible corona commences under the reduced barometric pressure at that altitude. This voltage is frequently referred to as the "corona voltage," and the values given in the diagram are for equi-spaced three-phase lines. The other curves on the diagram are for normal barometric pressure at sea level. For single-phase or two-phase this voltage must be multiplied by 1·16.

The connection between the flashing-over spark and the visual corona voltages is very interesting, and is shown for a particular case by the two curves in Fig. 1.170, in which the electric pressure in kilovolts at which the phenomena appear is plotted against the distance apart of the wires. The latter were of polished copper 0·654 cm. in diameter, and the observations have been corrected to standard pressure (76 cms.) and to a temperature of 25° C. For the closer [illegible] the spark passes before [illegible] corona appears, the [illegible] the latter beginning at 50,000 volts with the wires at about 11 cms. apart. From that point onwards the spark voltage rises rapidly along a straight line with the rise of the voltage, and reaches 130,000 volts at 35 cms. distance apart of the wires. The curve for the corona rises much more slowly, and at 60 cms stands at 72,000 volts. Thus, for wires close together the passage of the spark is the first evidence that the stress has exceeded the elastic limit of the dielectric, whilst for greater distances the corona is the first evidence of excessive stress. The critical spacing seems to be when the distance apart of the two parallel wires is somewhat greater than about thirty times their radius.

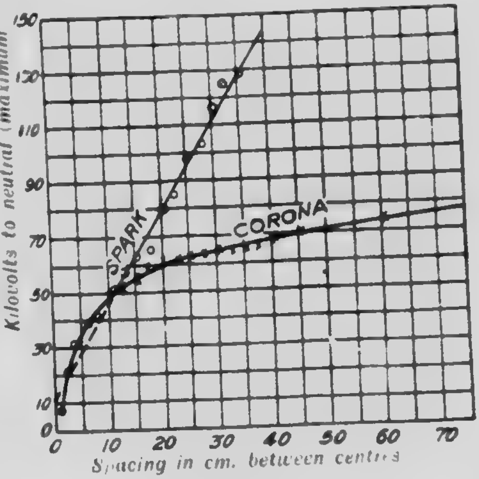

Fig. 1.170.—Effect of Spacing on Spark and Corona Voltage.

Voltage Limitations. To sum up, it is not easy as yet to specify what factor will fix the limit to which the voltage may be raised for high-voltage overhead transmission. More than one possible limiting factor is coming into view, and the final limit may be determined by the rapid increase with the voltages of (*a*) the losses due to the corona, (*b*) the difficulties of controlling the charging currents and transient phenomena of surges, etc., met with in alternating current circuits, or (*c*) the extra costliness, as partly shown in the foregoing pages, of almost every item of the equipment of the transmission system from the step-up transformers at the generating station to the point at which, by step-down devices, more manageable voltages are reached at the distribution end.

IV.—UNDERGROUND CABLES

We pass now to the other general method (*see* page 1[illegible]1) of transmitting and distributing electric power, namely, by means of properly insulated conductors laid underground; but before dealing with the details of the laying of conductors so insulated it will be convenient to devote a separate section to the consideration of the cables which have been found useful for the widely different cases occurring in practice. These cables consist of one or more copper conductors, insulated with suitable materials, assembled together to make a single rope or cable and protected by various coverings, insulating, non-insulating, and metallic, from injury which may be caused by the conditions and the environment under which they will be used.

The cable consists of the conductor with its insulating sheath, technically known as the "core," of which there may be one or more in any given cable. In "multicore" cables the bunched cores are usually surrounded, as a whole, by a further insulating sheath outside which there are one or more protecting layers of fibrous materials, such as jute, hemp, etc., and a continuous metallic shield made of lead, and, finally, when necessary, heavy steel armouring The number of protecting layers and their composition have special regard to the circumstances under which the cable is to be used.

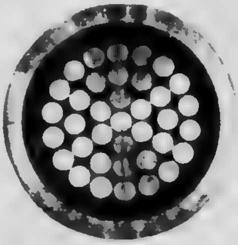

Fig. 1,180.—"Henley" Single-core Low-voltage Paper Cable.

The Core.—The single or stranded *conductors* which, *with an insulating sheath*, form the core, have already been described (*see* pages 1101 to 1105, *ante*). The conductor in underground cables is almost invariably made of *copper* annealed and quite soft; it has a higher electrical conductivity, and is more pliable than hard-drawn copper. *Aluminium* is not much used, because its increased cross-section for a given conductivity per unit length necessitates a larger insulating sheath, which is expensive. The comparative lightness of aluminium is not of much importance for underground work, as the supports are not likely to give way, and, as a matter of fact, owing to the greater quantity of insulating material and the greater weight of metallic sheathing, cases arise in which the aluminium conductor cable is actually heavier than the equivalent copper conductor one.

In *single-core* cables the conductor and its sheath are naturally in the middle of the cable, as shown in Fig. 1,180, which represents full-size the section of a simple low-voltage (600 volts) cable with paper insulation and lead-sheathed. There are thirty-seven conductors stranded together, each having a diameter of 0·118 inch (about No. 11 S.W.G.), the total sectional area being 0·4 square inch.

Multicore Cables.—For many purposes, both in transmission and in distribution schemes, more than one conductor is necessary, and in such cases there are many advantages from the point of view of capital expenditure, and otherwise, in placing the various conductors in one cable, which thus becomes a multicore cable.

The chief varieties which occur in practice and for which standard cables are listed by most cable-making firms, are shown in cross-section in Figs. 1.181 to 1.189. As we are at present only concerned with the assembling of the cores in the cable, simple low-voltage cables have been chosen to illustrate the methods adopted. The cables are all paper insulated, lead-sheathed "Henley" * cables, and are not armoured.

Where two conductors are required the cable can either be built up of two single-conductor cores twisted together side by side, or the two conductors can be concentric, one being placed inside the other with a proper thickness of insulation between. The first case is illustrated in Figs. 1.181 and 1.182. In Fig. 1.181 two nineteen-strand copper cables, paper-insulated, and forming two cylindric cores, are placed side by side and twisted together; the circular section is filled in with wormings round which an additional cylinder of paper insulation, $\frac{1}{20}$th inch thick, is laid and the lead sheath drawn over the whole. The separate wires are No. 14 S.W.G. (0·080 inch diameter), and each stranded copper conductor has a cross-sectional area of 0·094 square inch. The weight is 139 cwt. per mile.

It is obvious that in the arrangement shown in Fig. 1.181 much valuable space is wasted inside the cable which might be utilised to carry additional copper wires. Fig. 1.182 shows another pattern of twin cable in which, without increasing the over-all size, the stranded conductors consist each of nineteen No. 13 (diameter 0·092 inch) wires. The nineteen wires are arranged to have a semi-circular cross-section as shown, each wire being of elliptical, and not of circular, section. The cross-sectional area of copper is increased by 33 per cent. to 0·125 square inch, with a corresponding increase in current-carrying capacity; the same thickness of insulation is used, and with a slightly smaller total diameter the weight of the cable per mile is 142 cwts., or only 3 cwt. heavier than the last. The economy effected is obvious, and, to put it another way, a carrying capacity equal to that of the cable shown in Fig. 1.181 can be obtained with a cable similar to Fig. 1.182, but only 1·06 inch in diameter and weighing 113½ cwt. per mile, the insulation being of the same thickness in each case.

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* "Henley" cables are manufactured by Messrs. W. T. Henley's Telegraph Works Company Limited, at North Woolwich, London, E., and at Gravesend.

The other type of two-core cable is the "concentric," of which an example is given in Fig. 1.183. In this type the two conductors, which are the + and − conductors of a two-wire circuit, are of the same cross-sectional area; but the outer one, being spread over a comparatively large periphery, usually consists of more numerous and finer wires than the inner. In Fig. 1.183 the inner conductor consists of nineteen strands, each 0·101 inch in diameter, having a total cross-sectional area of 0·150 square inch. The outer conductor consists of twenty-seven wires laid in a single cylindric layer concentric with the inner conductor, each conductor being about 0·084 inch in diameter. The thickness of insulation is 10 per cent. (0·090 as against 0·10) less than in the preceding cases, and the lead coating somewhat thinner, the weight per mile being 150 cwt. The quantity of copper and the carrying capacity are 20 per cent. greater than the conductors shown in Fig. 1.182, and 60 per cent. greater than those shown in Fig. 1.18

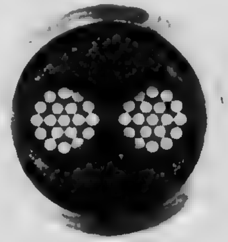


Fig. 1,181.

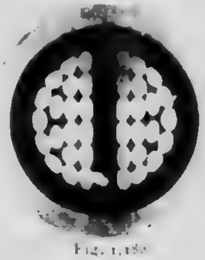


Fig. 1,182.

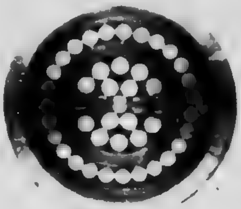


Fig. 1,183.

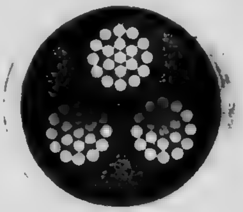


Fig. 1,184.

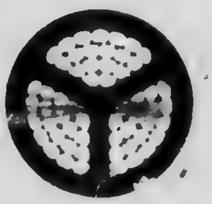


Fig. 1,1[illegible]

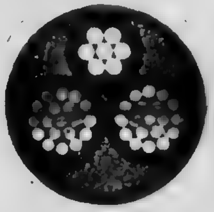
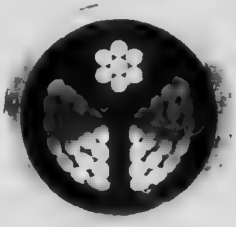


Fig. 1,1[illegible]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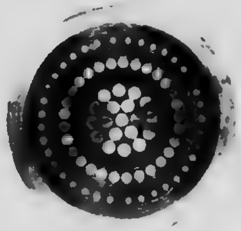
Fig. 1,1[illegible]

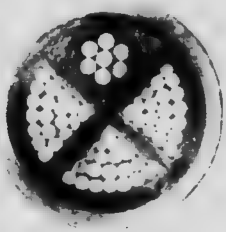
Fig. 1,1[illegible]

Sections of Henley's Multicore Low-voltage Paper Cable

For both continuous and alternating current work three wires are frequently needed, and again a multicore cable is a better engineering solution than three separate single-core cables. As before, the cables may consist of three single cores twisted together, or of triple concentric conductors insulated from one another.

Examples of the first type are given in Figs. 1.184 to 1.187. In Fig. 1.184 the three single-conductor cores are exactly similar, as would be required if the cable were used for three-phase working. Each core consists of nineteen No. 15 S.W.G. (diameter, 0·072 inch), with 0·090 inch thickness of insulation between conductors and between conductors and the lead sheath. The three cores are twisted together and the section made up circular with wormings before the outer layer of insulation is laid on. The cross-sectional area of copper in each conductor is 0·075 square inch, and the total weight per mile is 141·3 cwt.

In Fig. 1.185 the three cores are also exactly similar, but the cable differs from the last in the same way that Fig. 1.182 differs from Fig. 1.181. In this case, however, since three cores have to be accommodated the section of each core is a triangular circular sector and not semi-circular as in Fig. 1.182. Each core contains nineteen No. 14 (diameter, 0·080 inch) copper strands instead of No. 15's, as in Fig. 1.184, notwithstanding the fact that a greater thickness (0·10 inch) of insulation is used. The cross-sectional area of each stranded conductor is 0·094 square inch, as against 0·072 square inch in Fig. 1.184, an increase of 30 per cent. The weight per mile is 146·4 cwt., an increase of less than 4 per cent. only.

The next cable (Fig. 1.186) is for three-wire continuous current working, in which, as explained elsewhere, the third or neutral wire has usually one-half the cross-sectional area of either of the other two. In Fig. 1.186 the two main conductors are exactly similar to the conductors in Fig. 1.184, but the third conductor has only half the sectional area (0·0375 square inch), and consists of seven strands each about 0·083 inch in diameter. The weight per mile is 127·4 cwt. as against 141·3 cwt. in Fig. 1.184.

The corresponding cable to the last, in which the main stranded conductors are of a triangular section so as better to utilise the space, is shown in Fig. 1.187. As in previous similar cases the cross-section of copper is increased, the change this time being for the main conductors from 0·075 square inch to 0·100 square inch, a net gain of one-third. The neutral wire which remains, of the ordinary circular section, is correspondingly increased to 0·050 square inch, and not much space is left to be filled with wormings. The neutral is a seven-strand conductor, each wire being 0·097 inch in diameter. Thicker insulation is used than in the last case, and the weight is increased to 141·16 cwt. per mile, or by rather over 11 per cent. for an increase of 33⅓ per cent. in the carrying capacity.

A triple concentric cable, also for three-wire continuous-current working, is shown in Fig. 1.188. The main conductors are the inner and middle ones, and the neutral wire is the outer conductor. The inner conductor has nineteen strands of No. 16 s.w.g. wires, each 0·064 inch in diameter; its total sectional area is 0·06 square inch. The middle conductor of the same total sectional area consists of twenty-nine wires, each 0·051 inch in diameter in a single layer concentric with the middle wire. The outer or neutral conductor has a sectional area of 0·03 square inch, and consists of thirty-seven wires each of No. 21 s.w.g. wire, 0·032 inch in diameter. The thickness of the insulation is 0·080 inch in each ring, and the carrying capacity is less than in either of the two last cases, but the weight is also less, being 118·6 cwt. per mile.

The last case to which attention need be called is that of a four-core cable suitable for three-phase transmission for star-connected systems in which a fourth or neutral wire is run. The section is shown in Fig. 1.189. The three main conductors are arranged each in a triangular section and consist of nineteen strands of No. 15 s.w.g. wire, each 0·072 inch in diameter, the total sectional area being 0·075 square inch. The neutral conductor is of circular section and consists of seven strands each of wire 0·083 inch in diameter, and having a total sectional area of 0·0375 or one-half that of each main conductor. The thickness of insulation is 0.090 inch, and the spare space, which is not great, is filled up with wormings. The weight per mile is 142 cwt.

For purposes of comparison, the whole of the cables in the illustrations given on page 1144, all of which have now been described, are of the same kind, that is, they are lead-sheathed multicore cables with paper insulation. The drawings are to scale, and the outer diameter of the cable is nearly the same in each case. In all but the concentric types the cores are twisted together with a lay which increases the length and the resistance by 2 per cent. In the concentric cables the wires of the rings which form the outer, and in one case the middle, conductor are wound on spirally with a lay which in their case also increases the resistance by 2 per cent. The maximum pressure at which the cables are to be worked is 600 volts, and the thickness of the insulation is practically the same in all cases; from the different disposition of the conductors the insulation resistance between lines will, of course, be different, but in every case there is an ample margin of safety. The comparison between the carrying capacities of the different cables is so interesting from the point of view of the effect of the arrangement of the conductors, that for convenience of reference the various data are collected together in a table. It will be understood that the cross-sectional area of a conductor is a measure of its current-carrying capacity.

TABLE XVI.—UTILISATION OF SPACE IN MULTICORE CABLES.

([illegible])

Type of Cable.*	Overall Diameter.	Sectional Area of each Copper Conductor.	[illegible] Dielectric.	[illegible] Sheath.	W[illegible]
	In.	Square In.	In.	In.	[illegible]
Twin circular conductors	1·30	·094	·10	·100	130
Twin semi-circular conductors ...	1·17	·125	·10	·110	142
Concentric (two conductors)	1·23	·150	·09	·09	150
Three-core circular conductors	1·20	·075	·09	·100	141·3
Three-core circular conductors (one neutral half section)	1·22	·075 ·0375	·09	·100	127·4
Three-core triangular conductors	1·20	·094	·10	·100	140·4
Three-core triangular conductors (one neutral half-section)...	1·17	·100 ·050	·10	·100	141·2
Four-core (one neutral half-section (Mains triangular, half-section circular)	1·30	·075 ·0375	·09	·100	142
Triple concentric (one neutral half section) ...	1·17	·060 ·030	·08	·100	118·6

The Insulator or Dielectric.—The question of the best material for the dielectric of an underground cable is a highly complex and technical one, and in the space available it will only be possible to indicate the main outlines of the problems presented by the properties, favourable and unfavourable, of the materials which are most widely used at the present time. The chief electrical properties sought for in the ideal dielectric are

(*a*) High insulation resistance.

(*b*) Low dielectric constant (specific inductive capacity).

(*c*) High dielectric strength.

In addition to these purely electrical properties, various mechanical, chemical, and other physical properties are desirable or even necessary. Amongst these may be mentioned:

(i.) Chemical stability.

(ii.) Non-hygroscopic or waterproof.

(iii.) Flexibility and elasticity, leading to freedom from cracking when bent.

(iv.) Mechanical stability, such as resistance to tension, compression, and other mechanical strains, together with freedom from softening.

(v.) Freedom from serious change in any of the above properties due to rise of temperature within working limits.

Insulating Materials.—Many and various materials have been tried from time to time as insulators for underground cables, but modern practice has in effect reduced the number to three, viz.

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* *See* Figs. on page 1144.

(α) India-rubber, pure and vulcanised.

(β) Fibrous materials, such as specially prepared paper impregnated with insulating compounds and sheathed with lead.

(γ) Bitumen, carefully purified and vulcanised, either by itself or in conjunction with impregnated fibrous materials.

Gutta-percha, so invaluable for submarine cables, is not included in the list.

It is not easy to compare even so few as three classes of materials with respect to the complicated properties referred to above, especially when, as in each of these cases, the material has a complex structure which, without destroying its general character, is affected by the different manufacturing processes to which it may be subjected during its preparation and whilst it is being applied to the conductor. A rough attempt at comparison is made in a convenient form for reference in the annexed table :

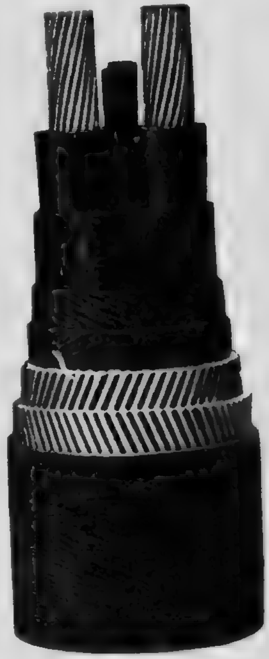
TABLE XVII.—COMPARISON OF VARIOUS CABLE-INSULATING MATERIALS

Material	Specific Resistance (cm. measure) Megohms.	Dielectric Constant (Specific Inductive Capacity)	Dielectric Strength. Kv. (R.M.S.) per cm.	Chemical Stability.	Water [illegible] Properties.
(*a*) India-rubber, pure	10·9 × 10^{15} at 24° C.	2·12 to 2·34	160 to 500	Deteriorates slowly	Non-hygroscopic
(*b*) " vulcanised	1·6 to 6·2 × 10^{15} at 24° C.	2·69 to 2·94	300 to 1,100	Deteriorates more slowly	Non-hygroscopic
(*c*) Paper, impregnated	11·9 × 10 at 15° C.	2·0 to 3·35	100 to 250	Excellent	Hygroscopic
(*d*) Bitumen, vulcanised	8 to 50 × 10^{15} at 0° C.	2·68	—	Excellent	Non-hygroscopic

The *rubber cables* are made of pure Para rubber or of high-grade vulcanised india-rubber, so treated as to secure a maximum of strength and elasticity compatible with maximum insulation resistance and dielectric strength.

The *fibrous insulating material* is usually a strong, long-fibred *paper*, such as manilla paper, entirely free from metallic particles, carbon spots, or deleterious substances such as straw, wood, or other ligneous fibres, and well dried before it is used. This paper is laid spirally on the conductor and then impregnated with an insulating compound which is plastic at ordinary temperatures, and has no tendency to drain away from the cable or to alter its distribution in the cable under the higher temperature conditions which may obtain when the cable is heated by the current.

The *bitumen* cables are insulated with a high-grade vulcanised bitumen combining elasticity and mechanical strength and applied in tubular form to the conductor under high pressure. It is quite non-hygroscopic, and, compared with rubber and lead-sheathed paper, is much cheaper, but ordinary commerical bitumen is physically a very viscous fluid, and has the properties of a fluid as modified by great viscosity rather than those of a solid. Thus, under steady mechanical forces it flows as a fluid, but very, very slowly, and its tendency to flow is increased by rise of temperature under which its viscosity is diminished. By prolonged industrial researches, however, manufactured vulcanised bitumen has been evolved whose physical and other properties are very much better for cable-making than ordinary bitumen. It is claimed that this prepared bitumen is more resilient when hot than at ordinary temperatures, that its inertness to atmospheric and chemical influences appears almost infinite, and that it is very durable. In early bitumen cables the conductors were liable to be decentralised, the conductor by its weight slowly but surely pushing its way downwards through the viscous material. It is claimed that this fault has disappeared from the modern cables. To distribute the mechanical stresses more uniformly and to minimise further this tendency, Messrs. Glover and Co. interpose between the separate cores in twin- and three-core cables, a shown in Figs. 1.181 to 1.187, a cradle of specially prepared vulcanised bitumen of high resilience. This cradle and the bitumen of the cores are shown shaded differently in Fig. 1.162, which is from a photograph of the cable in section, whilst Fig. 1.160 exhibits the cable with the various layers stripped, or telescoped as it is called, and Fig. 1.161 shows the core only with the "Cracore" divider projecting between the conductor. The other protecting sheaths, including the steel armouring, are described fully later on. Cables in which this device is used are known under the trade name of "Cracore," derived from the "cradle" separator used to support the core.



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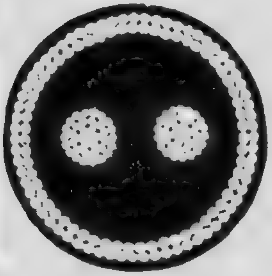


[illegible]

Glover's [illegible]

Deterioration Due to Internal Causes.—Before considering the protection of the insulated core from adverse external influences, a brief reference may be made to the internal causes of deterioration of the essential properties of the dielectric.

Influence of Copper.—The most curious of these internal causes of deterioration is the influence of copper on india-rubber in contact with it. This influence has been referred to as the "catalytic oxygen-carrying properties of copper," a phrase which does not help us very much. Whatever the explanation, there is, however, no doubt about the effect—namely, that even the purest rubber in contact with copper slowly perishes and loses its distinctive properties. We are told that this is due to the oxidation of the rubber molecule, and it is a well-known fact that a small change in any of these highly complex organic molecules frequently results in an enormous change in the physical properties of the body of which they are the constituent parts.

Fortunately, this particular effect can be effectively prevented by *tinning* the copper—that is, by covering its surface with a thin but quite continuous layer of tin, a metal which, it is found, does not act similarly upon rubber. Tin (*see* page 751, Vol. I.) is not so good a conductor as copper and its use increases the resistance as calculated from the diameter on the assumption that the conductor is of standard copper. It is also, as a rule, a more expensive metal than copper, and thus on both grounds as little tin as will be effective is used. The Engineering Standards Committee has decided that *one per cent.* increase of resistance may be allowed on all tinned copper conductors between the diameters 0·118 inch (No. 11, S.W.G.) and 0·028 inch (No. 22, S.W.G.) inclusive. For larger diameters the effect on the resistance of the same thickness of tin is not so serious.

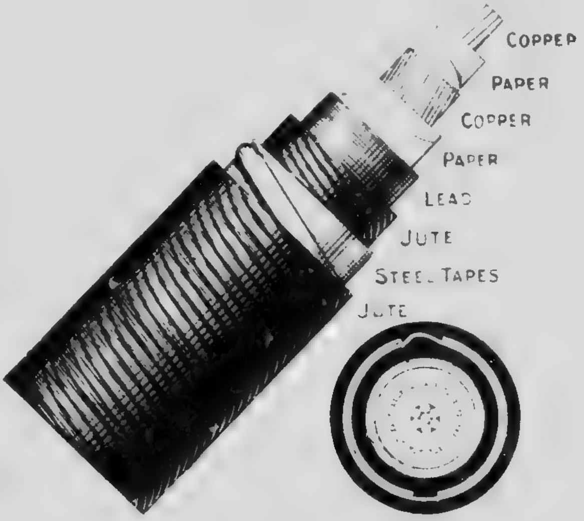
In certain flexibles and special wires the copper is not tinned, but cotton lappings are interposed between the copper and the rubber; this method of protection is, however, very sparingly used.

Influence of Sulphur.—Another internal source of trouble is the *action of the sulphur* present in all vulcanised dielectrics *on the metal* of the conductor with which the dielectrics come into contact, whether the metal be copper or tin. The process of vulcanising (i.e. treating with sulphur) enhances certain properties of the dielectric, but is not without disadvantages, of which this is one. The difficulty does not arise in paper-insulated cables, because the paper is not vulcanised.

In *rubber cables* it is met by placing a thin layer of *pure rubber* next to the metal, and outside this the vulcanised rubber. In vulcanised bitumen cables the general inertness of bitumen is often relied upon to resist the action, special steps being taken to prevent moisture being introduced by a creeping action between the strands of the conductor. Sometimes, however, a thickness of paper or jute is first applied over the conductor, thus separating the sulphur from the metal, but having the disadvantage of introducing hygroscopic material in direct contact with the conductor.

Protection of Cores.—If any of the insulated cores described above were laid in the ground simply covered over in a shallow trench, it would probably soon succumb to one or more of the adverse external influences to which it would be exposed. These influences are many and varied, and perhaps will be most readily followed by reference to an actual cable supplied with the most usual protective devices.

An example is given in Fig. 1,193, which shows a cross-section and longitudinal view of a Glover* concentric paper insulated cable protected with a lead sheath, steel tapes, and a jute serving. The [illegible] view shows the various layers cut away step by step so as to expose the layers below in regular sequence. The cable core proper consists of the two copper conductors with their paper insulating coverings already described. Immediately outside these is the *lead sheath*, the function of which is to supply an absolutely watertight flexible covering, such a covering being necessary because of the more or less hygroscopic nature of the paper insulation. The lead [illegible] drawn down as a solid tube under heavy hydraulic pressure [illegible] core below. Before entering the lead press the [illegible] a bath of insulating compound. In tropical countries [illegible] sometimes applied to other than paper cables to repel the [illegible] insects.



[illegible]

The lead sheath is served with [illegible] yarn, which may be, for small-diameter cables, in the form of braid. The cable is often passed through a bath of preservative compound after the application of the impregnated jute yarn. On this as a protecting bed steel armouring is laid either in the form of steel tapes or steel wires to protect the cable, if laid direct on the ground, from mechanical injury due to careless excavating or other causes which, in the absence of the steel armouring, might lead to the various other coverings being cut through and to the conductors being exposed. In the particular case shown in Fig. 1.193, two steel tapes are wound on spirally as shown more clearly in Fig. 1.194, which represents a three-core paper-insulated cable being so overwound outside the first layer of jute yarn. The width and thickness of the mild-steel tape used depend partly on the size of the cable and partly on the degree of protection deemed necessary. In the cases shown there are two layers wound on spirally one over the other, so as to break joint with one another. The inner or lower tape has a central rib indented longitudinally upon it, as can also be seen in the sectional drawing of Fig. 1.193. The outer tape is flat, and just fills the space between successive turns of this central rib. There is thus secured not only the extra protection due to two thicknesses of steel, but also the presence of the rib fixes the relative positions of the spiral joints on the two tapes, and tends to prevent their relative displacement during the handling and laying of the cable.

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* The "Glover" cables are manufactured by Messrs. W. T. [illegible] Manchester.

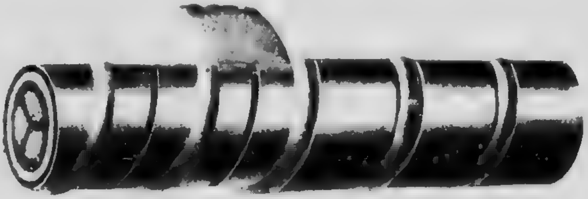


Fig. 1.194.—Glover's Cable with Ribbed Steel Tape Armouring.

An example of protective armouring with steel wires instead of tape is given in Fig. 1.195 which shows a "Glover" three-core vulcanised bitumen double-wire armoured cable. The three separate cores after being taped with distinctively coloured tapes are laid up together round a bitumen centre with a suitable lay and sheathed all over with a solid tube of vulcanised bitumen compound to form the "three-core" core. Each core is taped with two spirally wound layers of cotton tape thoroughly impregnated with bituminous compound, and outside this a bedding of jute yarn or braid as above. No lead sheath is required, as the dielectric is non-hygroscopic. The double wire armouring consists of two concentric layers of galvanised mild steel wires served upon the jute bedding; both layers are wound on spirally with a long lay, the outer lay being in the reverse direction to the inner.

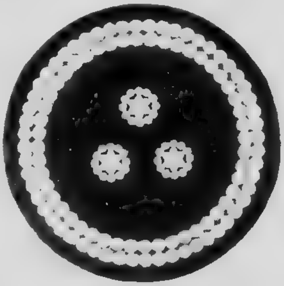


Fig. 1.195.—Cable with Double Steel Wire Armouring.

The specification for the armouring of "Henley" (see page 1144) paper cables is that, for cables of less than 0·5 inch diameter over the lead sheath, the armouring is composed of galvanised steel wires 0·072 inch in diameter (No. 15 S.W.G.). Larger cables are armoured with two layers of steel tape thoroughly coated with a protective compound before being applied to the cable, the thickness of the steel tape being—

0·030 inch for cables from 0·5 to 0·75 inch diameter.
0·040 inch for cables from 0·76 inch to 2·0 inches diameter.
0·060 inch for larger cables.

Heavy steel wire armouring is, however, used for quite large cables made by this firm.

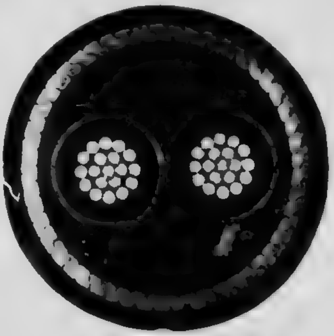


Fig. 1.106.—Henley Cable Fitted with Lock-coil Armouring.

Where great mechanical protection is required, Henley cables are furnished with the special type of lock-coil armouring shown in Fig. 1.106. The steel wires which are laid on spirally have the cross-section shown, and when in place form a solid sheath of steel which is served with jute in the usual manner. This method is expensive, but is the strongest form of armouring as yet devised for cable protection.

In certain circumstances, the Board of Trade requires that in lead covered cables the lead shall be earthed and electrically continuous throughout. One method of satisfying this condition in practice consists in providing the lead [illegible] with [illegible] special [illegible] in two ways: that is, either (i.) by copper tape wound on the dielectric immediately under the lead, or (ii.) by galvanised steel wires laid directly on the lead covering. Both copper and steel are much better conductors than lead (see page 751, Vol. I.), and a thickness of 10 mils (0·016 inch) in the copper, or steel wires 0·100 inch in diameter, give a sufficiently conductive "earth sheath." Illustrations of these methods are given in Figs. 1.107 and 1.108 respectively. In Fig. 1.107 which gives details of method (i.), a 0·125 sq. in. three-core three-phase cable is shown with copper strips not less than 0·016 inch in thickness laid round the core under the lead and in direct contact with it. For the particular size of

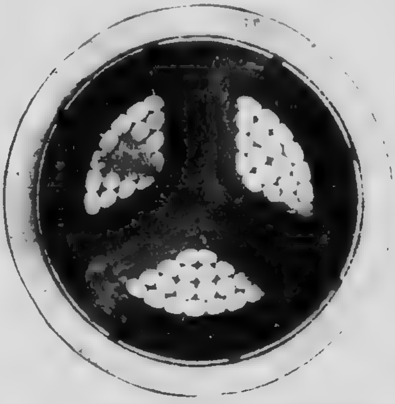
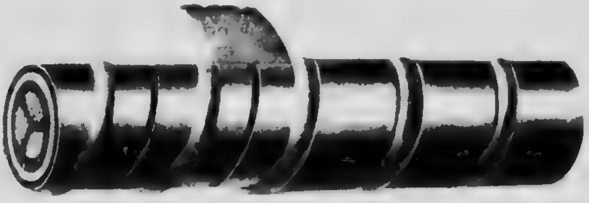


Fig. 1.107.—Cable with Copper Earth Strips under the Lead Sheath.

protect the cable, if laid direct on the ground, from mechanical injury due to careless excavating or other causes which, in the absence of the steel armouring, might lead to the various other coverings being cut through and to the conductors being exposed. In the particular case shown in Fig. 1.193, two steel tapes are wound on spirally as shown more clearly in Fig. 1.194, which represents a three-core paper-insulated cable being so overwound outside the first layer of jute yarn. The width and thickness of the mild-steel tape used depend partly on the size of the cable and partly on the degree of protection deemed necessary. In the cases shown there are two layers wound on spirally one over the other, so as to break joint with one another. The inner or lower tape has a central rib indented longitudinally upon it, as can also be seen in the sectional drawing of Fig. 1.193. The outer tape is flat, and just fills the space between successive turns of this central rib. There is thus secured not only the extra protection due to two thicknesses of steel, but also the presence of the rib fixes the relative positions of the spiral joints on the two tapes, and tends to prevent their relative displacement during the handling and laying of the cable.



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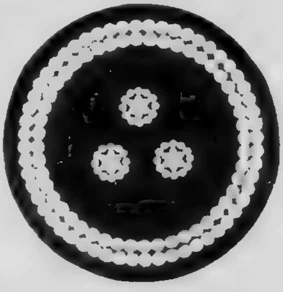

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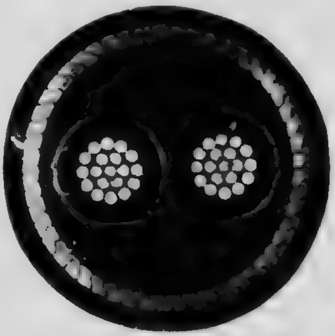

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Where great mechanical protection is required, Henley cables are furnished with the special type of lock-coil armouring shown in Fig. 1.106. The steel wires which are laid on spirally have the cross-section shown, and when in place form a solid sheath of steel which is served with jute in the usual manner. The method is expensive, but is the strongest form of armouring as yet devised for cable protection.

In certain circumstances, the Board of Trade requires that in lead-covered cables the lead shall be earthed and electrically continuous throughout. One method of satisfying this condition in practice consists in providing the lead covering with a special "earth sheath" in one of two ways; that is, either (i.) by copper tape wound on the dielectric immediately under the lead, or (ii.) by galvanised steel wires laid directly over the lead covering. Both copper and steel are much better conductors than lead (see page 751, Vol. I.), and a thickness of 16 mils (0·016 inch) in the copper, or steel wires 0·100 inch in diameter, give a sufficiently conductive "earth sheath." Illustrations of these methods are given in Figs. 1.107 and 1.108 respectively. In Fig. 1.107, which gives details of method (i.), a 0·125 sq. in. three-core three-phase cable is shown with copper strips not less than 0·016 inch in thickness laid round the core under the lead and in direct contact with it. For the particular size of

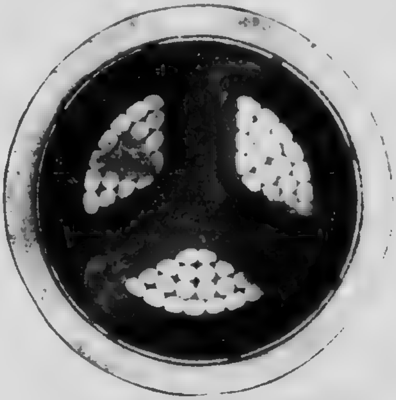

Fig. 1,107.—Cable with Copper Earth Sheath under the Lead Sheath.

cable shown, which is heavily insulated to stand a voltage of 11,000 volts, the copper adds over a ton weight per mile, and a corresponding increase in price. The second method (ii.) is illustrated in Fig. 1.198, which shows a 20,000-volt 0·05 sq. in. three-core cable, with an earth sheath consisting of steel wires not less than 0·10 inch in diameter laid *over* the lead and in direct contact with it. In this case the sheath adds 87 cwt. per mile to the weight, but the extra cost is not so high as in the preceding case, because of the cheaper material used.

As a final example of an armoured modern distribution cable for heavy currents, Fig. 1.199 gives a full-size section of a three-core "Henley" distribution cable supplied to a South Wales colliery company. Each of the copper conductors has a sectional area of 0·8 sq. in. and consists of ninety-one strands of 0·108-inch copper wire insulated with a thickness of 0·10 inch of impregnated paper. The three cores are laid up together in the usual way, and the interstices filled with jute wormings. Another layer of paper dielectric 0·8 inch thick is then laid on, and outside this the copper tape which forms the "earth sheath"; the lead covering 0·15 inch thick is then drawn on. This is served with tarred jute yarn to form a bedding for the armouring and to protect the lead from electrolysis. The armouring consists of a single layer of stout steel wires, served overall with a final covering of tarred jute yarn treated with a preservative compound. This cable has a diameter of 4 inches, and is designed for a working voltage of 3,000 volts.

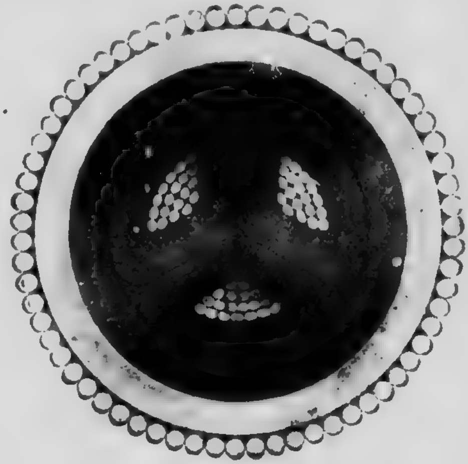
Fig. 1,198.—Cable with Steel Wire Earth-sheath over the Lead Sheath.

In works, collieries, etc., it is often desirable for temporary purposes to use a loose trailing cable rather than one permanently installed in ducts or otherwise. In such cases heavy steel-armoured cable is neither necessary nor convenient, and the requisite mechanical protection can be provided by tarred rope, leather braiding, hard-cord braiding, or in other ways. Such a trailing cable is shown in Fig. 1.200 in the form of a three-core Glover cable with an additional and smaller fourth core, which acts as an earth wire. The cores are rubber insulated, and are surrounded by a vulcanised-bitumen ribbed sheath moulded so as to fit between the insulated cores and providing a bedding electrically more suitable than any form of fibrous packing. The bitumen sheath is surrounded by a serving of bitumen tape outside which there is a layer of compounded jute braid surrounded by the serving of whipcord braiding as an external protective covering.

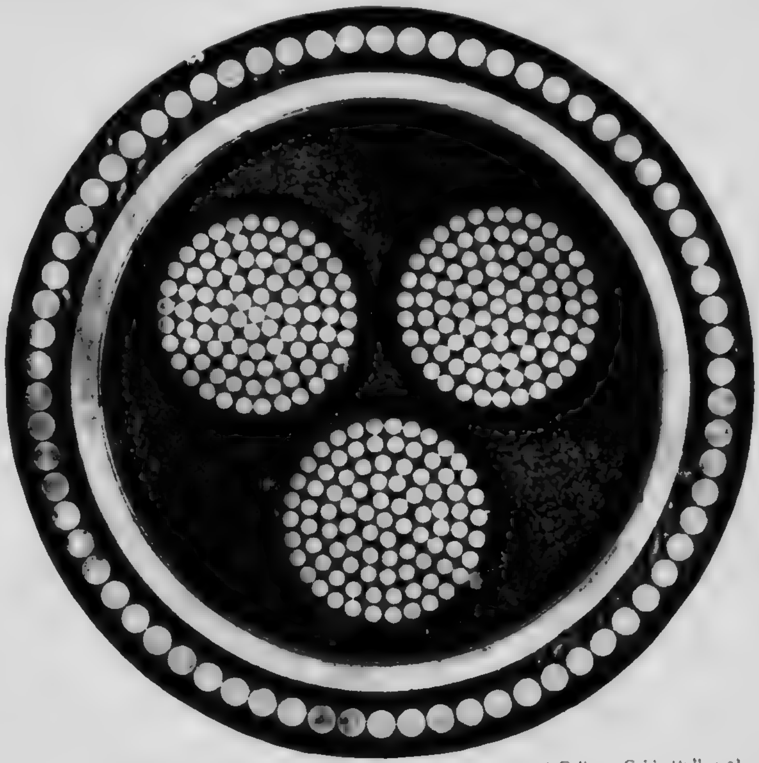

Fig. 1,199.—**Three-core, Paper Insulated, Lead Sheathed, Armoured Colliery Cable (full size).**

This external protective covering has to withstand the hard usage consequent on the cable being dragged over rough places, encountering all kinds of obstacles, and also the damage caused by falls of roofs in collieries, as well as the general rough usage of the factory or mine. The finished cable should be practically waterproof, so that it can be left lying about

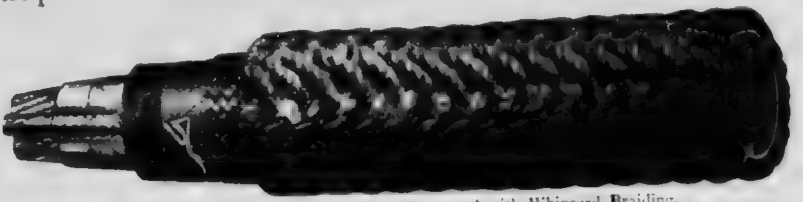

Fig. 1,200.—**Glover's Trailing Cable Protected with Whipcord Braiding.**

in damp situations without injury. Various such coverings have been standardised for Henley cables. Thus there are braids made of mattress twine, or hard cord, or raw hide, or leather strips about $\frac{1}{16}$ inch wide, and a special compounded hard-cord braid interlaced with galvanised-steel wires.

Design of Cables.—The foregoing descriptions of the types of cables in actual use will enable the reader to appreciate a few general remarks on the use and design of cables, the subject being interesting as showing the importance of keeping in view the elementary electrical laws set forth in Vol. I.

A cable consists of a conductor using a solid dielectric for an insulator, whereas in an overhead line, except at the supports, the insulator is gaseous, being the atmosphere in which the conductor is immersed. We have, in dealing with the "corona" and cognate phenomena, described how the electric properties of the dielectric affect high-voltage transmission with overhead lines. The properties depending on the dielectric which have to be considered in cable transmission are the insulation resistance and the capacity at all voltages, and the dielectric strength at high voltages. Some references have already been made to these in the earlier parts of this section (pages 1.147 to 1.150), and the object in returning briefly to the subject here is to mention one or two points in which they affect the design of the cables.

The insulation resistance and the capacity are, as in other cases, proportional respectively to the "specific resistance" and the "specific inductive capacity" of the dielectric, and it is important that the first should be as high as possible, and the second, in A.C. working, as low as possible. In both cases there is a geometrical factor which for cables contains the term

$$\log \frac{d_1}{d_2}$$

in which d_1 is the outer diameter and d_2 the inner diameter of the dieletric sheath. In the resistance formula this term (which becomes zero when $d_1 = d_2$) is a multiplier, and in the capacity formula it is a divisor. In each case, therefore, it should be as large as possible, a condition which would be attained (i.) by using a great thickness of dielectric, and (ii.) by keeping the diameter d_2 as small as possible—i.e. by using a solid, (not stranded) conductor—necessarily, however, of the proper current-carrying section.

The satisfying of condition (i.) is limited by considerations of cost, which increases rapidly with increased thickness of insulation; whilst condition (ii.) places copper above aluminium (*see* page 1102) as the more suitable material for the conductor, because for the same value of $\frac{d_1}{d_2}$ the quantity of the dielectric will depend upon the square of d_2.

When, however, we examine the factors which determine the *dielectric* *strength* of a cable, we find the conditions changed. The dielectric strength of the material is specified as the voltage required to rupture a flat slab 1 centimetre or 1 millimetre thick, the former voltage being 4·5 times the latter when the material is homogeneous. When the bounding surfaces are not flat the tendency to rupture increases with their curvature, as has been fully explained elsewhere (see Vol. I., pages 82, 128, 132, etc.). Now of the two dielectric surfaces in a cable the inner one has the greater curvature, and it is there that the material is most severely stressed. In a single-core cable of given current-carrying capacity the larger aluminium conductor has the advantage over the smaller copper one, as the dielectric will stand a higher breakdown voltage. The point, however, is only of importance when high voltages are used, for up to 10,000 or 11,000 volts the maximum stresses are quite low provided the surface of the conductor next the dielectric is smooth and of uniform curvature.

Design of Inner Conductor. For high voltage work it will be scientifically and may be commercially advantageous to re-design the conductor so as to reduce the stresses on the dielectric, and Figs. 1.201 and 1.202 show in section two such conductors designed for a 50-kilovolt cable, so as to give a stress of 50 kilovolts (R.M.S.) per cm. in the dielectric. The figures are taken from a paper* by Mr. C. F. Beaver, and in each the outer diameter is the same (0·80 inch), and the stranded copper conductor shown by the small circles has approximately the same current-carrying capacity. In Fig. 1.201 a hollow lead tube, 0·536 inch outer diameter, is surrounded by twenty-four 0·082 inch copper wires, over which is drawn a lead sheath 0·05 inch in diameter; whilst in Fig. 1.202 a central stranded conductor of 19/15 S.W.G. copper wires is surrounded by a paper wrapping 0·117 inch thick, outside which are twenty-four 0·053-inch copper wires, which in their turn are covered by a lead sheath 0·05 inch thick. This lead sheath in each case presents a smooth surface to the dielectric, and has a much smaller curvature than if it were drawn over a stranded copper conductor of say 19/16 S.W.G., which would have nearly double the curvature and about the same current-carrying capacity.

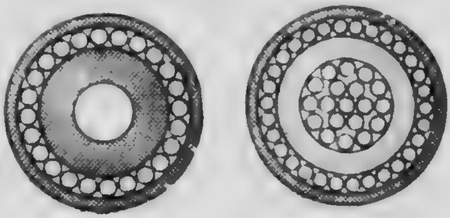
Fig. 1.201. Fig. 1.202.

Special Forms of Conductors.

Grading the Dielectric. The reader will have gathered from the foregoing that in a single-core cable with a perfectly homogeneous dielectric subjected to a high voltage, the slope of the potential, and therefore the stress on the dielectric, is greatest near the conductor, and diminishes outwards to the sheath. The danger is therefore that if the voltage is forced up, the dielectric will give way close to the conductor before the average voltage is reached at which the dielectric would break down if the slope of the potential were uniform. This led Colonel O'Gorman in 1901, and others since, to advocate that the dielectric should be graded in successive layers of different materials, so that either (i.) the dielectric strength of each layer shall be proportional to the stress in that layer; or (ii.) by making the specific resistance of the inner layers lower than the average, so that the P.D. on these layers shall be reduced; or (iii.) by using materials for the inner layers of lower specific inductive capacity, so that the potential gradient in these layers shall be reduced.

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* *Journal of the Institution of Electrical Engineers*, Vol. LIII., p. 59 (1914).

The subject, though interesting, is obviously a very technical and complicated one, and considerations of space do not allow us to develop it here. The cost of manufacturing any of the graded cables indicated would be greater than that of a cable with a homogeneous dielectric, and practical men are not even yet convinced that the extra cost is justified, especially when the risk of the graded cable being less reliable than the other is taken into account. As a compromise the "*intersheath*" cable has been proposed. This consists in introducing into the body of the dielectric one or more metallic layers and of "anchoring" these at predetermined intermediate potentials. Between the different metallic layers different dielectrics properly graded would be inserted, but each dielectric would itself be homogeneous. Such an intersheath cable is shown in Fig. 1,203, which is also taken from Mr. Beaver's paper. The conductors are 10 15 S.W.G. copper wires surrounding a lead tube 0·06 inch thick, and themselves surrounded by a lead sleeve 0·05 inch thick. Surrounding this there is the first thickness of paper dielectric 0·545 inch thick, and the intermediate lead sheath, *s*, 0·05 inch thick, after which comes the second layer of paper dielectric 0·565 inch thick, and the outer lead sheath 0·160 inch thick. The total diameter is 3·27 inches, and the cable is designed for a working voltage of 75 kilovolts; the maximum stress in the dielectric at this voltage is [illegible] kilovolts per centimetre.

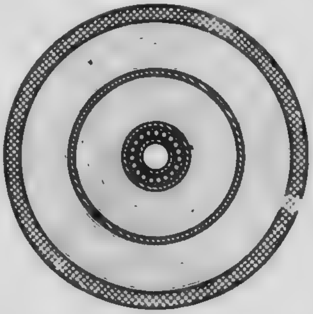
Fig. 1,203.—Single-core Cable with One "Intersheath."

An interesting constructional detail recently introduced in the "Glover" cables, with the main object of facilitating periodical inspection and examination of the condition of the cable, is the "test sheath," which consists of a thin conducting layer just inside but insulated from the outer sheathing and enclosing therefore all the line conductors. The use of this sheath will be explained later.

Testing Cables.—The methods of testing the insulation resistance and the capacity of cables, as well as testing for faults, are dealt with in other parts of this book, and therefore we need only refer here to the tests which are distinctive of cables which are required for power transmission. These are the tests for dielectric strength sometimes referred to as the break-down tests. For these the points agreed upon in the specification are the voltage to be applied in the test and the time occupied.

As regards the voltage, this should preferably be of the same type (A.C. or C.C.) as that under which the cable is to be used, but if a C.C. voltage is used for an A.C. cable or *vice versa*, it should be borne in mind that what matters in a breakdown test is the *maximum* voltage, and that the maximum voltage of an A.C. simple sine wave voltage is 1·41 times the R.M.S. voltage measured on the ordinary voltmeters. Keeping this in view, the actual test voltage, whilst greater than the scheduled working, should not be excessively greater, both because such excessive voltage is unnecessary, and also because, although it may not break down the cable, it may give rise to incipient faults which, in course of time, and even after the period covered by a guarantee, may develop into serious faults.

The most interesting cases are the high-voltage transmission cables, because in these the working pressures are near to what the dielectric can be expected to stand safely and continuously. Thus, for cables intended to work at 40 kilovolts it will be sufficient for the breakdown test if the test voltage be 100 kilovolts; for higher working voltages a somewhat lower ratio may be used—namely, about twice the working voltage.

As regards *time*, a mere "flash" test of a few seconds is not sufficient, as it may fail to discover incipient faults. A much longer period—say, not less than half an hour—is necessary to ensure that no such faults exist in the cable. This is more especially the case if the dielectric be thick and, if there is an intersheath in the cable, it should be used for the test, the proper intermediate voltage being applied. The existence of dielectric hysteresis is shown by the heating of the cable. In paper cables this heating becomes appreciable at A.C. stresses above 60 kilovolts per centimetre.

V.—UNDERGROUND CABLE LAYING

The cables described in the last section are, for either transmission or distribution purposes, placed underground, and the varied requirements which have to be complied with, and the still more varied local conditions, have led to the evolution of a few standard methods of running them.

The methods which are more or less in common use may be classified by saying that the cable may be laid—

(*a*) Direct in the ground. (This is known as "*direct laying*.")

(*b*) In troughs, afterwards filled with bitumen or some insulating compound. (These are known as "*Solid-laid*" systems.)

(c) In underground ducts or conduits into which the cables are drawn. (These are known as "*Draw-in*" systems.)

(d) On *brackets* in specially built or existing *subways*.

Direct Laying.—The first method (*a*) calls for little comment; but it is of the first importance to point out that cables so laid must be well "armoured," as described elsewhere (*see* pages 1151 to 1155), and that the metal of the armour must be surrounded with servings of jute thoroughly impregnated with bituminous or other compound calculated to protect the armour from chemical action in the soil. Such a cable is laid in a shallow trench, level and free from stones; deleterious matter, such as ashes, etc., likely to injure the cable must be removed, and soil for packing brought, if necessary, from elsewhere. The process of laying a cable by the side of a country road is shown in Fig. 1,204.* The cable is paid off the drum on the left as it is rolled along the road, and is simply lifted into the trench. If obstacles such as water or gas pipes are met with, it may be more desirable to cut and re-join the obstacle rather than to cut and re-join the cable. The cable should, in view of future contingencies, be arranged in a straight line at an even depth and distance from some easily recorded permanent reference line, such as a building line or a kerb. When laid, the cable should be covered first with one or two inches of selected soil, then with warning boards or tiles not less than 6 inches wide, and finally the trench should be filled in and well punned. The warning boards or tiles, the latter being preferable, are to attract the attention of subsequent excavators, so as to guard the cable from accidental injury from a pickaxe or other tool. A view is given in Fig. 1,205 of a shallow trench in an urban district with a large number of armoured cables in process of being laid direct. The view shows the tiles covering some of the cables already laid, some cables in the trench ready to be covered, and a cable being handled by the working gang and ready to be laid in the trench.

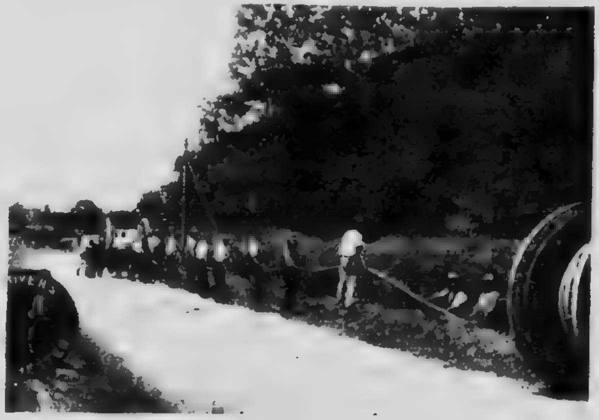

Fig. 1,204.—Direct Laying of a Cable in a Trench

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* For this and several of the other figures in this section the author is indebted to the courtesy of Messrs. W. Glover and Co., Limited, of Manchester.

Solid-laid Systems.—The principle underlying these systems was introduced early in the development of electric power distribution (see 1893 edition, page 631), as a cheap method of protecting the underground cable without the use of expensive armouring. This principle is to embed the unarmoured cable in solid bitumen or similar material contained in a suitable trough into which hot bitumen is poured *in situ* after the cables are placed in it. In succeeding years a great body of experience has accumulated, the faults of various methods of applying the principle have been tracked to their sources and eliminated by improvements in these details, small and great, upon which the durability of the practical systems depends.

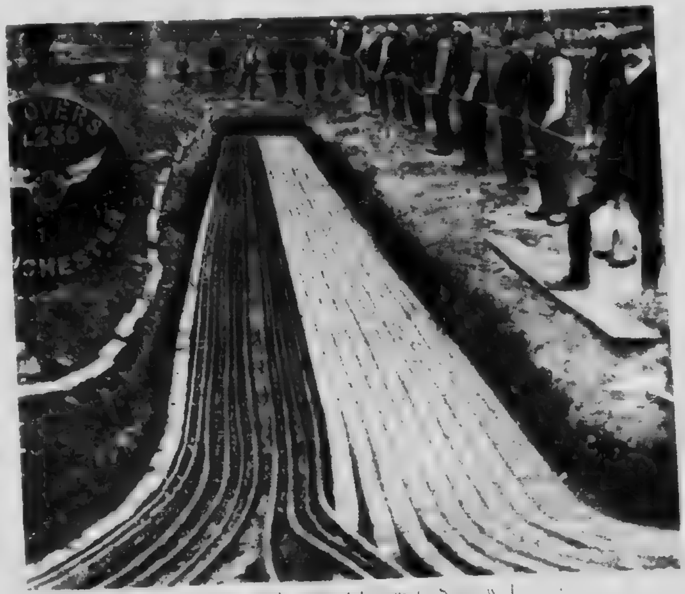

Fig. [illegible]

The material of the trough may be wood, cast-iron, concrete, asphalt, or earthenware. Of these, wood was the first to be used, and is still employed. Fig. [illegible] shows an early pattern, which, with somewhat thicker wood and more modern bridge pieces, would still be quite good. The wood now used is not less than $\frac{3}{4}$ inch thick, and is creosoted or otherwise treated with a preservative to protect it from the chemical action of the soil. The butt joint in a saddle is now usually replaced by a lap joint.

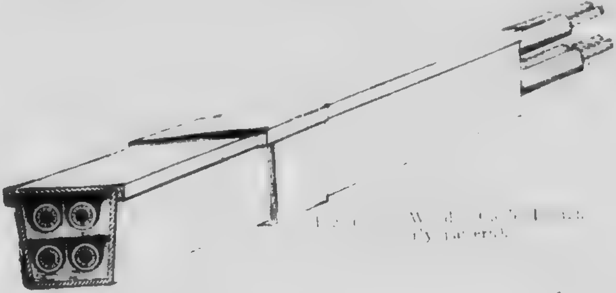

Fig. [illegible]

Cast iron troughs are usually made of metal ¼ inch or ⅜ inch thick, and in 3-feet and 6-feet lengths; the stock sizes run from 1½ inches wide by 1½ inches deep to 7½ inches wide by 3 inches deep. A side view and section through the joint of a standard trough are given in Fig. 1,207. The joint is a butt joint, the butt of one length resting in a lip on the lower surface of the following length, the two lengths being bolted together. Two patterns are shown for the cover. The process of laying the cables in such troughs as part of the distributing system of an urban district [illegible] shown in Fig. 1,208. No fewer than sixteen cables are being simultaneously laid in four parallel troughs preparatory to the running in of the warm bitumen. These cables, as in Fig. 1,206, rest upon bridge pieces, and are also kept apart by distance pieces above. *Cement* troughs and *asphalt* troughs are also used.

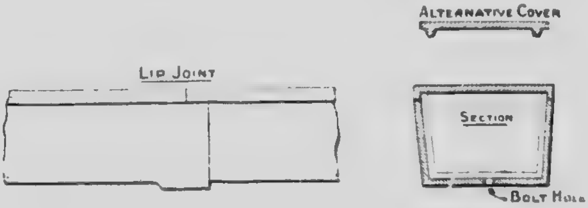

Fig. 1,207. Side View and Section of Cast-iron Trough.

Lastly, a *stoneware* trough, as made by Messrs. Doulton and Co., of Lambeth, is shown in Fig. 1,209. These troughs are made of hard-burnt glazed earthenware, and are either rectangular, as shown, or U-shaped. They are in 2-feet lengths with a spigot and socket joint, in which no cement is used, and are provided with covers made of the same material, with ribs to fit the inside of the trough. Special bends are made for curves, which must not be negotiated by breaking the straight troughs. As the lengths are short, they must be carefully bedded to ensure an even support throughout, and pockets must be cut to receive the sockets.

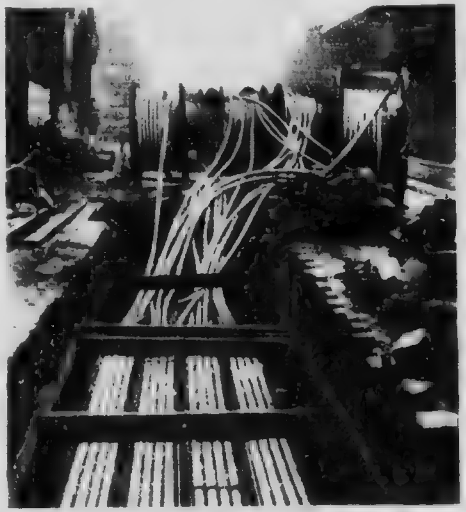

Fig. 1,208.—Laying Cables in Cast-iron Troughs.

Though wooden *bridges*, more properly called *separators*, as shown in Fig. 1,206, are still used, their use is not considered good practice, especially for lead-sheathed cables, where the lead rests upon the wood. The wood, however treated, is more or less hygroscopic, and sooner or later trouble, in the form of chemical action on the lead sheath. Porcelain or vitrified stoneware is much better for bridge pieces, though more expensive; they should be dipped in hot compound just before being placed in position. Asphalt is also used for bridges; it is non-hygroscopic, cheaper than stoneware, and does not, as might be expected, melt away when the hot bitumen is poured in.

Fig. [illegible] D[illegible] Stoneware [illegible]

Great care is required in laying a "solid" system. It should never on any account be laid in wet weather; the cable, the trough and the bridges should be quite dry, and the "material must always be stored in a weather-proof place until immediately before it is required."

The troughs being laid, and the cables ready on the side of the road, very hot bitumen is poured into the trough to the depth of ½ inch, and the bridges are placed in position not more than 18 inches apart, as can be seen in Fig. 121, which on the left of the trench shows a wooden trough and the bridges with the cables placed in position, which is the next stage in the process. The bridges should be absolutely dry and be dipped in hot bitumen thinned with creosote oil just before being placed in the trench, in which they should never be placed at joints between sections. The next process to that shown in the figure is the "filling in." The bitumen compound is heated to fluidity, with constant stirring, in a pitch boiler of convenient capacity for the work in hand. The filling in should be done gradually, and in three or four successive stages, and in the direction in which the cable is being laid, unless the trench is on an incline, in which case the filling in should be started at

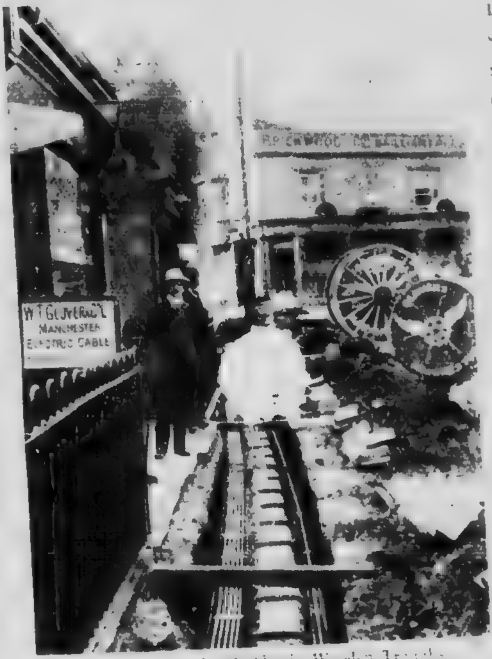

Fig. 121.—Laying Cable in Wooden Trough.

the lowest point. The final topping off should fill the trough to overflowing, and the cover should be pressed hard down into the bitumen whilst it is still plastic. If the filling-in be too rapid the copper and lead (if it be lead sheathed) of the cable will become dangerously hot, and will expand, causing the cable to buckle, and in extreme cases to rise right out of the trough. The trough should be covered with selected soil to a depth of 2 or 3 inches, the trench being then filled in and well punned.

Draw-in Systems. Another set of methods for laying underground cables consists in laying pipes or ducts in the ground with manholes at suitable positions and distances. When the system of ducts is completed the cables can be drawn in; hence these methods are known as "draw-in" systems. The cables for these systems are usually lead-sheathed, with a covering of jute over the lead to protect the latter from damage during the process of drawing in.

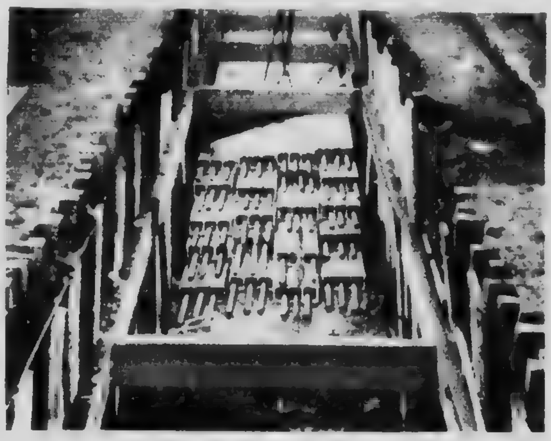
Fig. 1.211.—Laying of Doulton Stoneware Ducts.

The materials commonly used for the ducts are iron, stoneware, fibre, or cement. Where iron is used it is most frequently in the form of *cast-iron pipes* with the usual spigot and socket joints in 6-foot or 9-foot lengths, and varying in internal diameter from $1\frac{1}{2}$ inches to $4\frac{1}{2}$ inches, the metal being from $\frac{1}{4}$ inch to $\frac{11}{32}$ inch thick. The joints are well caulked with yarn and lead. The interior of the pipes should be smooth and free from all internal projections, and the exterior should be coated, before laying, with some preservative compound. *Weldless-steel pipes* in 40-foot lengths are also used; they are much thinner and lighter than cast iron, and the fewer joints are a distinct advantage; the exterior is protected against corrosion by a wrapping of impregnated jute cloth. *Wrought-iron pipes* are only used for special work, as they deteriorate rapidly.

Ducts or conduits of hard-burnt *glazed stoneware* are manufactured by well-known firms of potters and have been widely used. A trench in which a sixty-way Doulton conduit, manufactured by Doulton and Co., Limited, of Lambeth, is being laid is shown in Fig. 1.211. The ducts are rectangular in section, and are manufactured in short lengths with sets of two, three, four, or six duct ways in one moulding, and with sizes of duct ways varying from 2 inches to 4 inches square. Each length is bedded in cement mortar, and the joints are butt joints, a strip of canvas being wrapped round the joint to exclude the cement from the ducts. Mandrels are inserted, as shown, in the ducts at the joints during laying whilst the cement is setting. The sides of the trench are filled with concrete, with which also the whole nest of ducts is finally covered. Other forms of stoneware conduit are made by the same firm.

Another form of stoneware conduit made by the Albion Clay Company is shown in process of being laid in Fig. 1.212. These conduits are known as the "Sykes" conduits, and are made with two, three, four, and six duct ways, varying in diameter from 2 inches to 4 inches, and in four standard lengths up to 24 inches. Each set has a spigot and a socket end with composition linings cast on. The joint is made by pushing the spigot into the socket, which it fits so tightly that only a listing of Russian tallow and resin is required to make a good joint. Other details can be made out in the figure.

With stoneware conduits, which owing to necessities of manufacture are made in short lengths, it is very essential that the whole structure, when laid, should be evenly supported throughout its length. Special attention should therefore be paid to the preparation of the trench, and if deemed necessary a concrete foundation of suitable thickness should be laid. It is obvious that a subsidence of the supporting ground would lead to trouble.

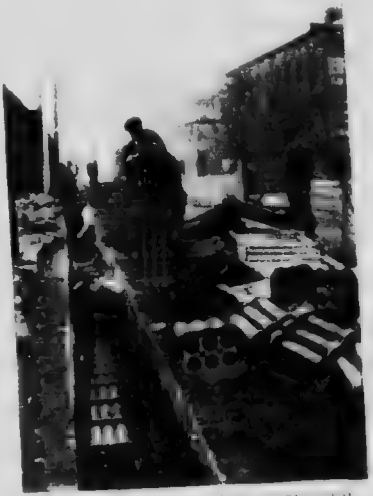

Fig. 1.212.—Laying of "Sykes" Stoneware Ducts.

Fibre conduits, consisting of fibre tubes saturated with a bituminous compound, are widely used in America. They are made in 5-foot lengths with a slip joint. The necessary number of duct ways is obtained by laying the single ducts side by side in concrete to form one solid block.

Slight bends in the route can be provided for in some forms of conduit by a bend in individual lengths or at the joints, but right-angled or big bends require the interposition of a manhole. An illustration of a gradual deviation in the route in laying "Sykes" conduits is given in Fig. 1.213. A four-way conduit is being constructed, and the necessary play for the deviation is obtained at the joints. As a rule a conduit should be run perfectly straight and carefully lined up. It should also be laid to drain towards the manhole, and all pockets in which water can collect must be avoided.

The *manholes* which are necessary in these systems should be carefully designed and constructed with the best materials and workmanship. They should be ventilated and drained, and if the latter be not possible a sump should be provided at the lowest point from which accumulated water can be bailed from time to time.

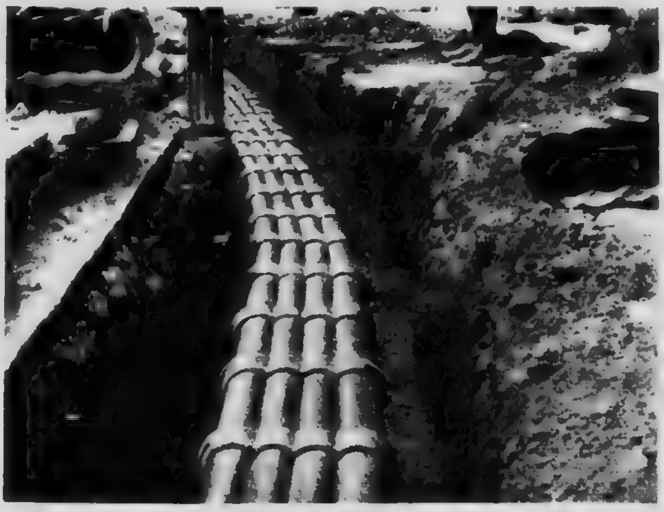

Fig. 1,213.—Four-way Stoneware Conduit showing Deviation in route.

These manholes are used as draw pits and for jointing consecutive lengths of cable. An illustration of such a manhole is given in Fig. 1.214, which shows a pit with four cables passing through it. Reference is made later on to the joints shown in this figure.

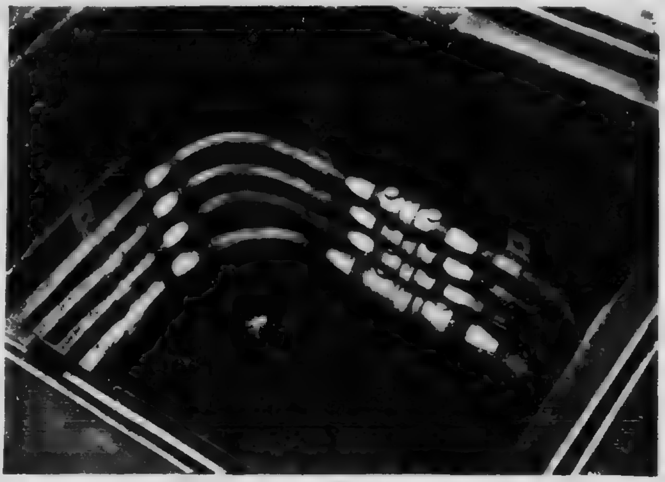

Fig. 1.214. Manhole for Drawing in and Jointing.

Subways. The most satisfactory method of running underground cables, from the point of view of accessibility and convenience, is to carry them on suitable brackets along a subway, as shown in Fig. 1.215, which depicts the interior of such a subway with some cables in position on the left-hand side, but with accommodation for many more.

Where a subway on the scale illustrated would have to be constructed for electrical transmission only, the cost would usually be prohibitive, but in early days of Niagara power schemes a subway was built for the high-voltage transmission lines from Niagara to Buffalo. More recently it has become the custom, in carrying out extensive improvement schemes, to construct suitable subways under the main thoroughfares, as in the subway shown in Fig. 1,215, *e.g.* in London in the Holborn Viaduct, Aldwych, and the Kingsway schemes and elsewhere. Such subways, besides being useful for electric-power cables, are available for telephone and telegraph services, steam heating, gas services, etc. One great advantage is the less frequent disturbance of the roadway with its consequent dislocation of traffic, by the various authorities and companies concerned.

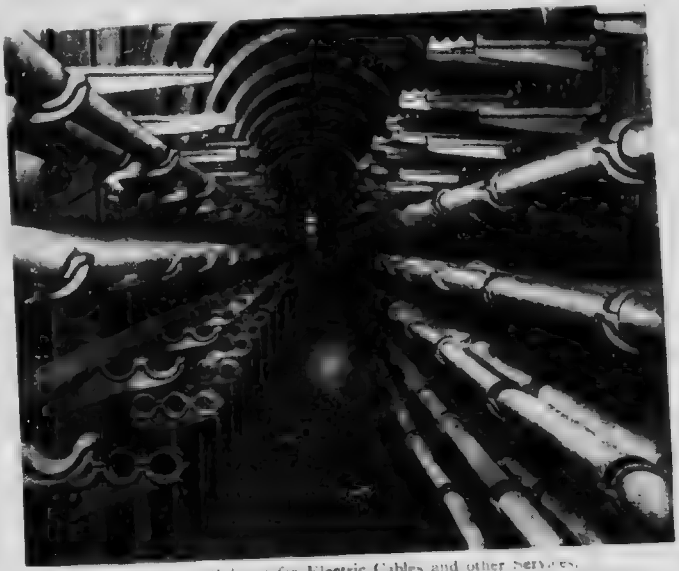

Fig. 1,215.—Subway for Electric Cables and other Services.

There are other cases in which subways constructed primarily for other uses are available for electric-power transmission. A notable type is that of underground railways where, along the sides of the already existing tunnels, the electric cables can be erected, occupying a minimum of space, and in which the absence of steam locomotives ensures a non-corrosive atmosphere. There is thus at hand an ideal location for the running of the feeders and the transmission cables which connect the generating station to the sub-stations.

Identification of Cables.—When numerous cables are laid in the same "run" a rapid means of identification is necessary. In manholes, metal or other labels may be used, but may sometimes become detached. At intermediate points the problem becomes more difficult. For lead-sheathed cables Messrs. Glover & Co. have solved the difficulty in their "Glovrib" cables by the simple device of moulding slight longitudinal projections or "ribs" along the exterior of the lead sheath. By varying the relative positions and numbers of these ribs the different cables of a large group can be made easily distinguishable.

Jointing.—It is obviously impossible, in the general case, owing to difficulties of manufacture, transport, and installation, to ensure that the insulated conductor or cable between two distant points shall be single and homogeneous throughout its length. At one or more points new lengths of cable have to be joined on to the lengths previously laid, and therefore some *process of jointing* has to be devised which will maintain the continuity of the conductor and the effectiveness of the insulation in both cases at a standard no lower than that obtaining in the cable itself.

These objects, so easily stated, are by no means easily attained under varied and complex practical conditions. There are three general methods, by one or other of which the problem can be solved, namely:

(i.) A jointing process by which the two ends are joined together by a joint which more or less nearly reproduces when finished the electrical and mechanical conditions of an unjointed and equal length of cable.

(ii.) The use of some mechanical fitting enabling junctions to be made more easily, if not quite so satisfactorily as in (i.).

(iii.) The use of a special joint box which incidentally may be made to attain some additional object.

Solid Jointing. Method (i.), which may be succinctly described as "solid" jointing, is far preferable to either (ii.) or (iii.), where a "straight-through" joint is required. It presents a much neater finish, and when well done is, electrically and otherwise, the best solution. The drawback lies in the difficulty of satisfactorily insulating the conductor at the joint, as this is an operation which can only be entrusted to a well trained, careful and skilful man, for if carelessly or unskilfully done it may be impossible by inspection or by any electrical or mechanical test to detect bad workmanship immediately after the completion of the work; sooner or later, however, trouble will ensue and the conseqeences may be very serious.

The actual jointing of the conductors is a simpler matter, though this requires much manipulative skill and practice where many stranded cables are being jointed. With all insulated conductors, before any actual jointing is commenced, the first step consists in stripping off the insulation, etc., for a sufficient distance from the end to give the length of bare conductor necessary for making the joint. This operation should be performed with clean, dry hands, and the exposed insulation should be protected with clean tape during the subsequent jointing operations. Various methods of **jointing conductors** are shown in Figs. 1.216 to 1.223. The simplest joint of all is a twisted joint for single copper conductors, such as is shown in Fig. 1.216, the wires being tinned, twisted together, and soldered. In this process resin only (not any soldering fluids) should be used as flux and ordinary tinman's solder, consisting of equal parts of tin and lead. The sharp end of each wire should be carefully filed down and fitted against the other wire, so as to have no tendency to cut into the insulation.

For stranded conductors several types of joints are in use. The "scarfed" joint shown in Fig. 1.217 is made by first soldering solid the ends of the strands of each conductor, and then scarfing them as shown. The two scarfed surfaces, first well tinned, are bound together with fine binding wire and well soldered. This, when well done, gives a finished joint very little thicker than the rest of the cable, which is an aim to keep in view in all jointing.

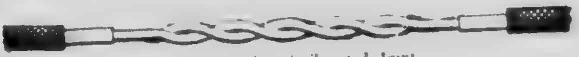

Fig. 1.216.—Simple Twisted Joint

In most methods for jointing stranded conductors, however, the strands are first separated as shown in Fig. 1.218, which illustrates the first stage of making a "married" joint. In this joint the well tinned ends are next twisted together as shown in Fig. 1.219 and then soldered. The result is not good, as the joint shows as an appreciable excrescence on the cable.

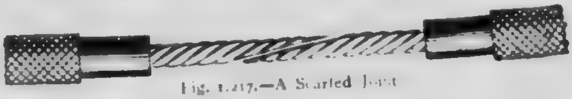

Fig. 1.217.—A Scarfed Joint

A better joint, especially for cables with nineteen or more strands, is the "telescopic" joint, a stage of which, for a thirty-seven-strand cable, is shown in Fig. 1.220. The conductor, having been bared and three inches allowed for overlap, a strong binder of thin wire is bound on each cable three inches from the end to keep the untouched wires in place. Then either (i.) the eighteen outer wires of the first conductor are splayed back and the eighteen outer wires of the second cut off short at the binder, or, alternatively, (ii.) each alternate wire of each conductor in this outer layer is cut off sharp by the binder. With the next layer of twelve wires operations (i.) or (ii.) are repeated, but on (i.), the cutting-off side is reversed. The inner core of seven wires is sweated solid on each conductor, and a scarfed or a butt joint got ready. Very accurate fitting is essential in all these operations. The cables being then laid together

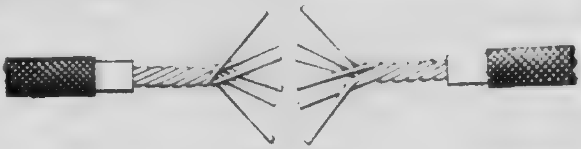

Fig. [illegible]

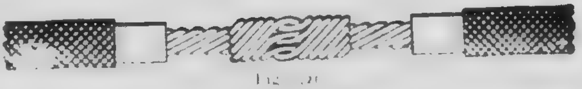

Fig. [illegible]
A "Married" Joint

the relative positions and numbers of these ribs the different cables of a large group can be made easily distinguishable.

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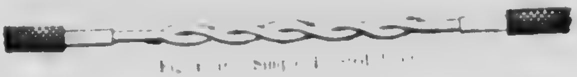

Fig. 1.217.—[illegible]

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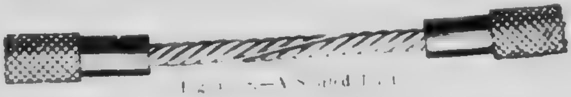


Fig. 1.218.—[illegible]

A better joint, especially for cables with nineteen or more strands, is the "telescopic" joint, a stage of which, for a thirty-seven-strand cable, is shown in Fig. 1.220. The conductor, having been bared and three inches allowed for overlap, a strong binder of thin wire is bound on each cable three inches from the end to keep the untouched wires in place. Then either (i.) the eighteen outer wires of the first conductor are splayed back and the eighteen outer wires of the second cut off short at the binder, or, alternatively, (ii.) each alternate wire of each conductor in this outer layer is cut off sharp by the binder. With the next layer of twelve wires operations (i.) or (ii.) are repeated, but on (i.) the cutting-off side is reversed. The inner core of seven wires is sweated solid on each conductor, and a scarfed or a butt joint got ready. Very accurate fitting is essential in all these operations. The cables being then laid together

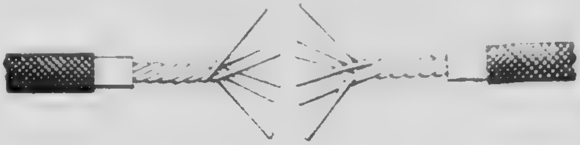


Fig. 1.220.

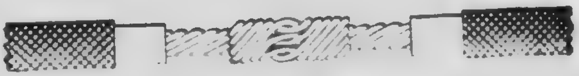


Fig. 1.219.—A "Married" Joint.

with the scarf or butt joint of the inner wires in place, the twelve intermediate wires are laid in place, bound down with tinned soft copper binding wires and sweated solid. When cooled the binding wire is removed and the outer eighteen wires are laid back in place, and in their turn are bound down and sweated. In this way, by careful manipulation, a soldered joint may be built up of approximately the same diameter of either conductor.

With concentric cables the procedure is more complicated, as the inner conductors must be jointed and insulated before the outer conductors can be dealt with. The difficulty then is to joint these outer conductors without injuring the insulation below. For such cables method (iii.) (page 1168) is preferable.

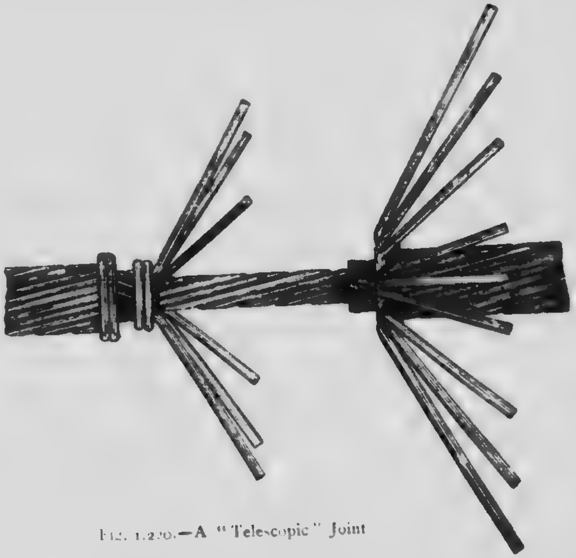


Fig. 1,220.—A "Telescopic" Joint

Although we have described briefly the above methods of jointing, like all workshop processes, they can only be satisfactorily learnt in the workshop itself, that is, by actual practice.

Insulating the Joints. The above remark is still more applicable to this, the next and much more delicate, process. Material of the same nature as that of the dielectric of the cable to be jointed should always be used. The satisfactory insulation of a joint in an *indiarubber* cable requires great experience, which can only be acquired in the workshop. No reading of a book can make a good jointer, and we shall not attempt to describe the process in detail. Put generally, the joint, carefully cleaned, is wrapped with pure rubber strip, vulcanised rubber compounds are then wound on the strip, and when the required thickness has been attained it is bound with rubber-coated linen tapes. The next process is that of vulcanising, which consists in immersing the joint bodily in liquid-wax compound and maintaining it at a constant temperature for a certain period of time, the apparatus used being known as a "cure" or "vulcaniser."

These stages of the process of insulating the inner conductor of a cable are illustrated in Fig. 1,221, in which, however, the actual object is to *seal* the ends of the rubber or bitumen cable, the conductor of which has been connected to a terminal thimble. In stage A, the conductor having been already bared and sweated into the thimble, the core and its protective braiding are shown as having been neatly trimmed down ready for the application of the insulating coverings. In B the conductor and core thus exposed have been carefully wrapped with the pure rubber, vulcanised rubber, insulating tapes, etc., mentioned in the last paragraph; C shows the insulating wrapping after being "cured"; and D after being neatly trimmed to give a good finish.

For *paper* cables paper sleeves for the joints can be supplied by the makers, or impregnated linen tapes can be used. Here again great care and practical skill is required, especially in view of the necessity of protecting the dielectric from the danger of the penetration of moisture.

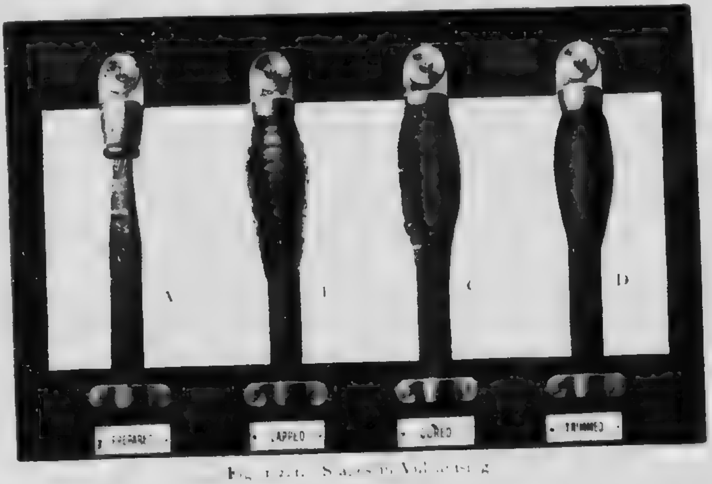


Fig. [illegible].—Stages in Vulcanising.

For *bitumen* cables, with the insulating tape supplied by the makers, the process of applying the insulating material is much more easily carried out, and only requires reasonable care. The final heating to form the whole into a homogeneous mass, can be effected by immersion in melted ozokerite or bitumen compound, and when this cannot be done hot compound may be baled over the joint, or even a blow lamp carefully used will give the required temperature, which is about 140° C.

Mechanical Fittings.—The second method (ii.) of jointing scheduled on page 1168 is more applicable to bare conductors, especially those of aluminium, than it is to cables. Nevertheless, such fittings are sometimes necessary on cables in positions which frequently occur in mines and elsewhere, in which naked lights are prohibited. They sometimes take the form of simple clamps or grub screws, which are not satisfactory either mechanically or electrically. In any case, such a fitting when covered with insulating material leads to a large excrescence on the cable after the process of insulating has been completed.

Necessity has led to the production of fittings which, if they cannot entirely remove the last-named objection, shall at least give satisfactory mechanical and electrical solutions. We propose to describe two of them, made by Messrs. Glover and Co., one simply dealing with the jointing of the metal conductors, the other covering up and neatly insulating the metallic joint on the type of cable for which it is designed.

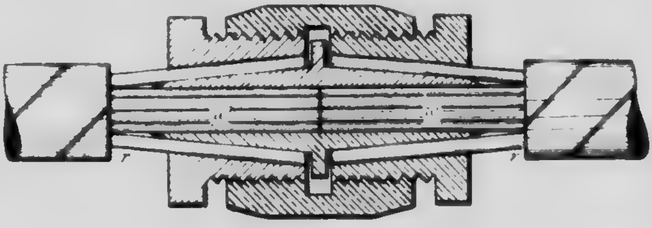


Fig. 1,222. Section of Mechanical Sleeve Joint.

The first of these, a purely mechanical connection for the two conductors, but preserving through numerous contact surfaces the electrical conductive continuity, is shown in Figs. 1,222 to 1,224. Of these, Fig. 1,222 shows a completed joint in section, and Fig. 1,223 a perspective view of the external appearance of the same on a smaller scale. Fig. 1,224 shows, also on a small scale, the component parts of the fitting. The inner wires *w w* (Fig. 1,222) of the stranded cable conductor are brought in line for a butt joint, and the outer wires *r r* are opened out. The split sleeve *s s* (Fig. 1,224) with its outer coned surfaces is placed over the butted inner wires, and the outer are arranged round the cones, the coned glands *g g* and the nut *n* having been first slipped over the ends of the cables. The glands are now drawn towards the sleeve, and the screw threads engage with the threads on the nut. On one side the threads are right-handed, and on the other side left-handed. On turning the nut in the right direction the glands are drawn therefore together, and compress the outer cover on to the surfaces of the split cones, the latter being thus pressed together on to the surfaces of the inner wires. The result is a joint mechanically strong, and electrically, owing to the effective surface contacts, as good a conductor as any other part of the cable, the fitting being made of high conductivity gunmetal when used on copper conductors.

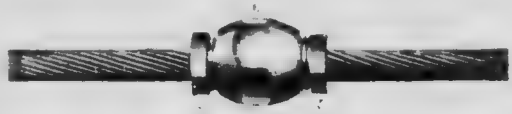


Fig. 1,223. Mechanical Joint Completed.

This fitting is also well adapted for aluminium conductors, in which case it is made of aluminium throughout, so as to avoid the electrolytic troubles referred to elsewhere.

The second fitting, shown in Figs. 1,225 and 1,226, is a cast-lead sleeve, and is rather of the nature of a simplified joint box, but it is in reality a mechanical fitting used for lead-covered cables, electrically connecting the lead sheathing of the two cables in a thoroughly satisfactory manner. It also provides facilities for insulating the joint in the conductors. In Fig. 1,226 the two halves of the sleeve are shown slipped back on the two cables, the conductors of which have been previously jointed and carefully insulated by one of the methods already referred to. Commencing with the jointing at the stage shown in Fig. 1,226 the next step is to place the two halves of the sleeve, first carefully cleaned, in position over the joint, and then to screw them together in such a way that the two filling holes *h h* are on top. The centre projecting flange is next beaten over, and the centre joint of the sleeve is wiped all round with metal to ensure it being watertight. The ends of the sleeve next to the lead of the cable are then gently beaten down upon it if there be any clearance, and a well wiped plumber's joint is made on each end. The sleeve is then filled with an insulating compound through one of the holes *h*, the other hole acting as a vent and the usual precautions being taken. Finally, these holes are closed with the screwed plugs, which are sealed down with solder. The finished joint is shown in Fig. 1,225, and some of these joints are shown in position in Fig. 1,214 (*see* page 1166).

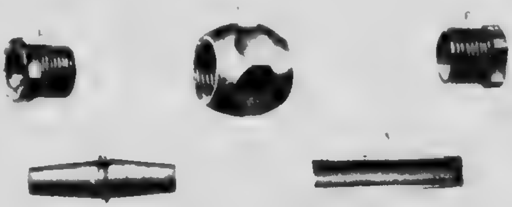


Fig. 1,224.—Component Parts of Metal [illegible]

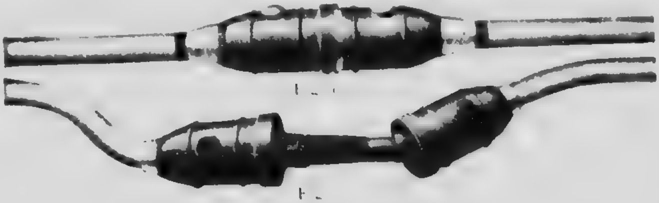


Fig. [illegible]

Fig. [illegible]

[illegible]

[illegible] Multicore Joints.—Methods similar to that just described can be used for joints on multicore cables, but the lead sleeve should be sufficiently long for the joints on the different cores to be staggered—that is, not to be opposite to one another in the closed sleeve.

Joints, however well and carefully made and insulated, should always be regarded and treated as weak places, and when the cable is to be used for high-voltage currents, still further precautions are taken to ensure that they are kept well apart. An interesting example of one method of taking such precaution, as designed by Messrs. W. T. Glover and Co., is given in Figs. 1,227 to 1,229, which show the details of a joint on a three-core cable for use on a 30,000-volt transmission line. The three cores, with an insulated joint on each, are shown exposed in Fig. 1,227. Before jointing, four hexagonal porcelain separators were slipped over the cable ends, and these are shown brought now into their final positions so as to hold the joints permanently apart from the adjoining cores. As already mentioned, the joints are so placed that they are not opposite one another, but each joint has nearest to it unbroken parts of the other two cores. In Fig. 1,228 it is seen that the lead sleeve is now in three parts—namely, two end parts coned as in Fig. 1,226, and a new intermediate part of cylindric shape with a rectangular opening on the top side. These parts are shown in position with the jointed cores and separators inside. The intermediate section has been carefully sweated or autonomously soldered to the two end sections. Fig. 1,229 shows the 30,000-volt joint with the insulating compound filled in and ready for completion by the sweating on of the cast-lead lid, which is also shown. With a non-hygroscopic insulating compound the result should be very satisfactory and reliable.

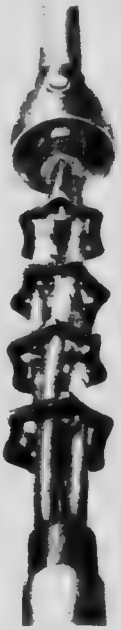


Fig. 1,227.

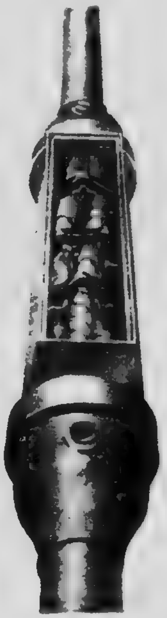


Fig. 1,228.

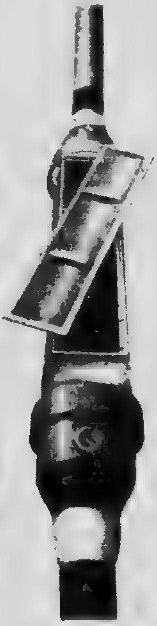


Fig. 1,229.

Joints in High-voltage Cables

Joint Boxes.—The third method specified on page 1168 for joining up successive lengths of cables is the use of *joint boxes*, which provide for the jointing of the conductors, and frequently also for their insulation. These boxes may be of two general types, namely—

(i.) Those in which the box simply takes the place of a straight-through joint, but renders the details of the joint accessible for inspection, and

(ii.) Those in which there are "disconnecting links" enabling successive lengths of cable to be quickly disconnected for testing or repairs.

The boxes must be so designed as to provide a ready and efficient means of terminating the cables, which run into them, and connecting the conductors to properly insulated fittings. In addition to providing an electric conducting bridge between the similar incoming and outgoing conductors, it is desirable by suitable bonding to connect metallically the armourings and the lead sheathings. The box should be watertight to ensure the maintenance of the insulation, and must be strong enough mechanically to protect the bridge and the insulation from injury. Many patterns of boxes are intended to be filled with an insulating bituminous compound, which is poured in hot and sets solid at ordinary temperatures. In this respect they resemble the "solid" systems of laying underground cables.

All these conditions are capable of being satisfied in various ways, and therefore there are on the market many patterns of joint boxes. It is practically impossible to describe all these, which only differ in small, but from particular points of view not always unimportant, details. The following boxes are selected from several patterns made by Messrs. W. T. Glover and Co., of Manchester.

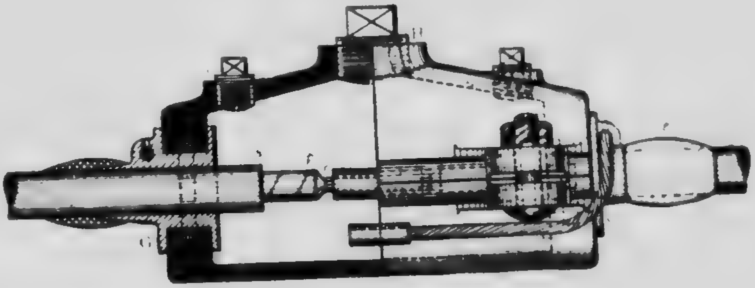


Fig. 1.230.

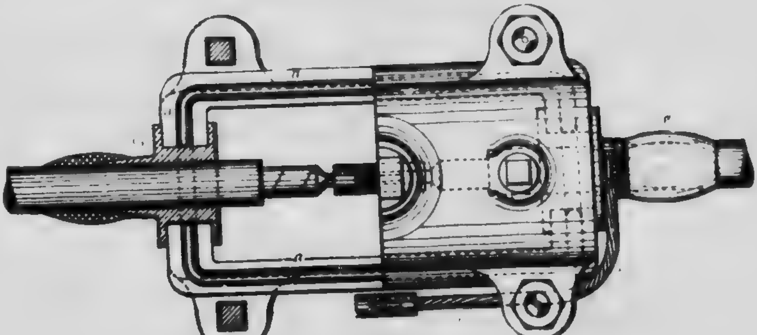


Fig. 1.231.

Glover's Single-core Cable Joint Box

The simplest type of such a box is one for a straight-through joint on a single-core cable. The "Glover" box of this type is illustrated in Figs. 1.230 and 1.231, of which Fig. 1.230 is an elevation and Fig. 1.231 is a plan. In each drawing one-half is shown in section, and constructional details are indicated. The box is of cast iron divided horizontally at the level of the axis of the cables into two parts, shown in Fig. 1,230. Each part carries four lugs by which the two parts can be bolted together. The cables are introduced through circular holes at the ends, into which brass cable glands G G are fitted, to which the cable is sweated. The details of the gland, as shown in both drawings, should be noted, and also that a plumber's "wiped" joint *g g* seals watertight the external orifice of the gland where the lead sheath of the cable enters it. The gland gives an ample bearing surface for the entering cable and avoids pinching. The gland also has a lug *l* into which the copper bond *b b* can be sweated. The lead sheath is trimmed off at *s* and the paper insulation at *p*, exposing the conductor at *c*. This conductor is electrically connected to the conductor of the other cable by one of the mechanical fittings described elsewhere. The facing edges of the two halves of the box are grooved as shown at *a a a*, and when the junction is complete, a suitably sized bitumen cord is placed on the groove and the top cover is clamped down. The bitumen cord, which is larger than is necessary to fill the groove, is compressed and makes the joint watertight. In the top cover are three holes, H, *h h*, which can be hermetically closed by screwed plugs. After the cover is clamped on and all the plugs removed, the box is filled with a hot insulating compound through the hole H, the contained air escaping through the holes *h h*. Various compounds are used with pouring temperatures varying from 133° C. to 167° C., and special precautions are observed to ensure that the air is not trapped in the compound. The compound cools in due course, and the final result is that the bare metal parts of the conductor and its joint fitting are left well embedded in a good insulating and watertight solid mass.

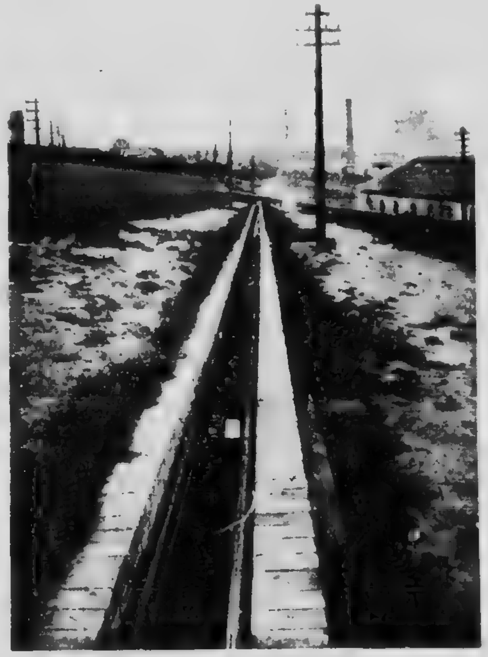
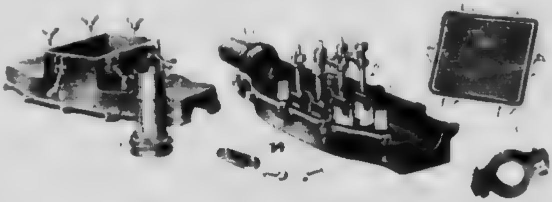


Fig. 1,232.—[illegible] Cables in a Brick Trench, showing a Joint Box.

The box, and the joint so made, may be in a manhole or may be in a trench such as is shown at A in Fig. 1,232, in which cables are seen in a brick trench constructed in not very good ground.

The joint box described above is of the simplest type, being for a single straight-through line; but it is obvious that such boxes can be elaborated to any extent as a mere matter of design following well-known principles and having due regard to the new conditions introduced, to which reference has already been made.

A requirement sometimes described and already briefly referred to is the insertion of a "*disconnecting link*" in the circuit of each conductor passing through the box. This link, as its name implies, is so designed as to be readily removable without interfering with the permanent connections of the cable conductors; when so removed the conductors on either side are isolated from one another. In practice this enables any section to be made "dead," so that repairs may be carried out on it without the adjoining section being put out of service. It also enables separate sections to be cut out for testing or other purposes, and is particularly useful in the event of a breakdown of one section of the system.



[illegible]

The general plan of a disconnecting link box is given in Fig. 1,233, which is a perspective view of a Glover three-core straight-through box. Each cable enters the box through an armour gland *g*, which, when the cable is in position, is packed quite watertight with suitable packing. The two glands are connected by a tinned copper band which ensures the electrical continuity of the sheathing. The cable end having been suitably trimmed, the three cores are separated, and each conductor is sweated into the socket *s* of one of the disconnecting pillars *p p*. There are six such pillars, each standing on a porcelain foot *f* which fits into a wrought-iron anchor bar and which insulates the pillar from the iron of the box. The pillars are arranged in three pairs, the pillars of each pair facing one another as shown, so that the two pillars can be connected by a metal link *l*, which can be clamped firmly on the pillar by screwed nuts. The pillar has a machined shoulder on which the link rests, and is threaded above the shoulder to receive the nut; the contact bases of the links are also machined, and there is a tapped hole in the centre of the link, in which an insulating handle can be fixed when the links have to be moved. The clamp *c* is for the purpose of clamping the ends of the armouring to prevent them getting loose.

All the permanent connections being made, the box is filled with insulating compound, as already described (*see* page 1176) to a level just below the contacts of the disconnecting links. It is interesting to note that a box for three cables each of 1 square inch conductor section requires 80 lb. weight of insulating compound. The joint between the upper and lower sections of the box is hermetically sealed with a bitumen cord gasket laid in the grooves provided, and the hand-hole cover is made watertight by a rubber gasket placed in a groove and compressed by the tightening up of the butterfly nuts.

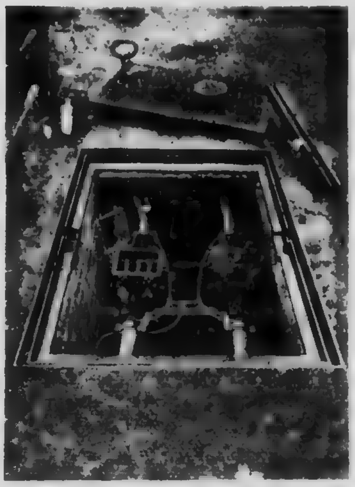


Fig. 1,234.—Manhole with Joint Boxes in Position.

These boxes can be laid in the ground in the general run of the cable, but are more accessible if placed in manholes, and are usually so placed. Fig. 1,234 shows an open manhole containing in circuit two boxes similar to that just described. The weight of the boxes is supported by bearers stretching across the manholes. The "jumpers" joining the cable sheaths should be noted.

It is often necessary, as explained elsewhere, to tap off from the straight run of a circuit a side line by what is known as a "Tee" joint, and for this purpose on heavy circuits a joint box is convenient. The box may

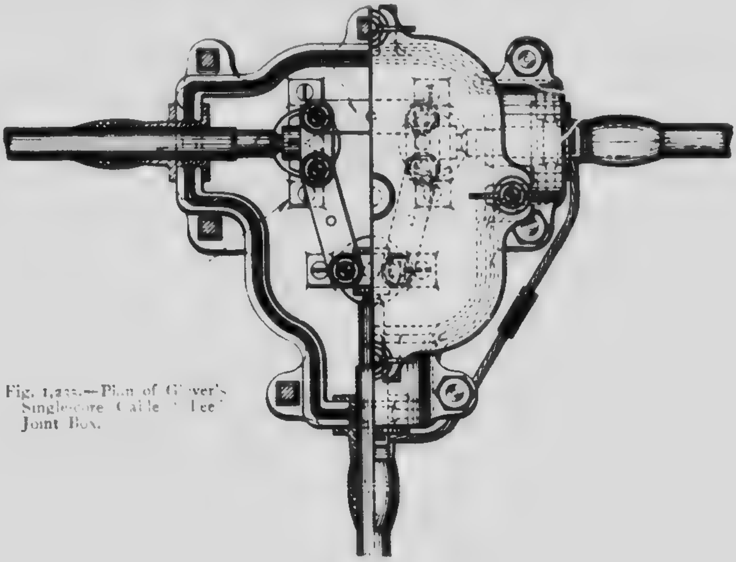


Fig. 1,235.—Plan of Glover's Single-core Cable "Tee" Joint Box.

be arranged either for a definite solid connection or for a connection through disconnecting links. One of the latter for a single core cable is shown in Fig. 1235. This figure is a plan, half of which is drawn in section. The chief modification, in addition to the fact that provision must be made for three cables entering the box, is that each disconnecting

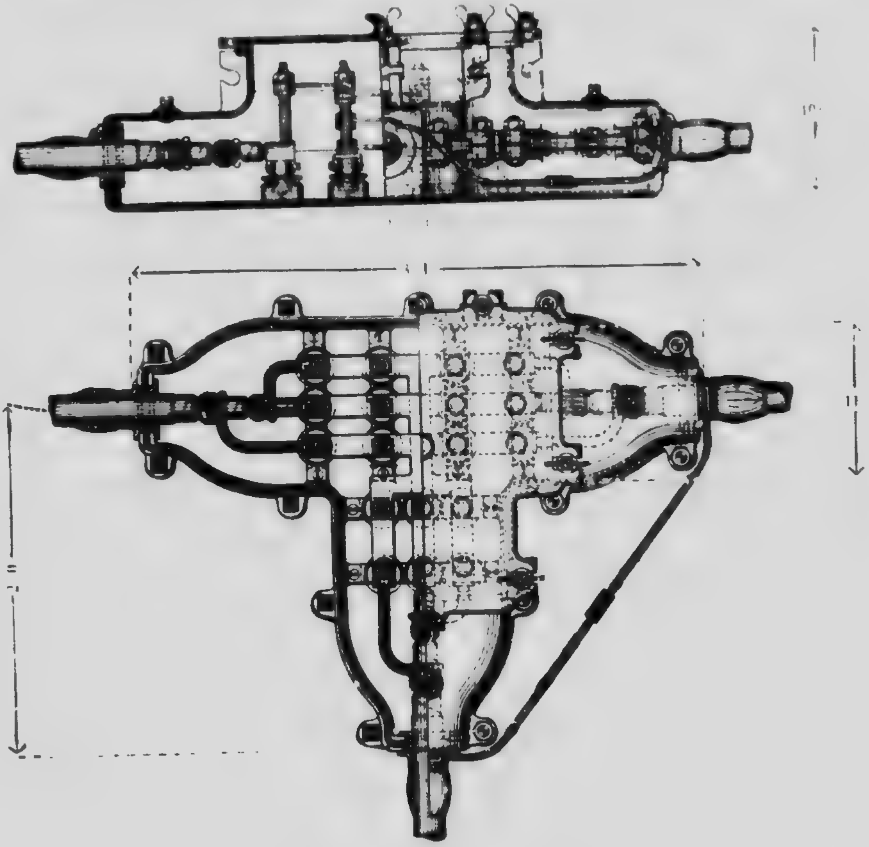


Fig. 1236

Glover's Three-core Cable Tee-joint Box.

pillar has to carry two disconnecting links so that it can be electrically connected to or disconnected from either of the other pillars. The three glands are all electrically connected by bonds, as partly shown. The other features of the box have been already described. The size for one square inch cables takes 27 lb. weight of filling compounds.

Standard boxes are obtainable for all the usual kinds of connections of both the "through" and the "disconnecting link" type, and for all the usual sizes of cables up to 1 square inch section of conductor. As a final example, Figs. 1.236 and 1.237 give details of a "disconnecting-link, three-way 'Tee'-joint box for triple-concentric cables." Most of the details can be followed from previous descriptions, but it may be noted that each cable requires six insulated disconnecting pillars, and that the inner nine of these, i.e. those towards the centre of the box, are permanently connected by stout copper straps run at different levels. The disconnecting links are between the [illegible]s of pillars for each cable, so that there are nine such links in all. The chief dimensions are given for the 1-square-inch size, which requires 195 lb. of filling compound.

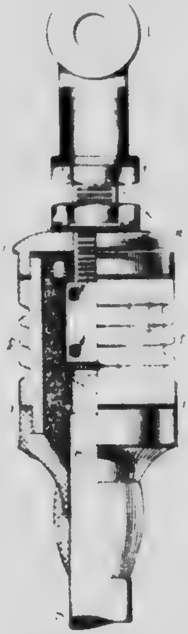
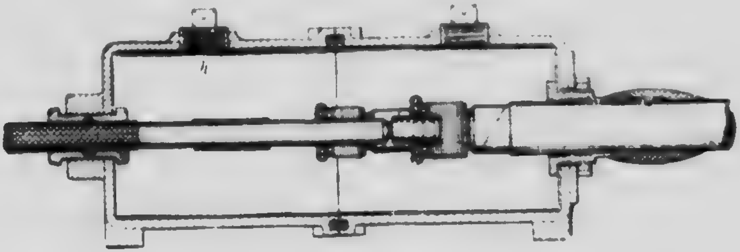


Fig. 1.[illegible] Glover's Sealing Cap for a Lead-sheathed Single-core [illegible]

Cable Terminals. Closely associated with the problems met with in jointing cables are the problems which arise when the course of a particular type of cable ends and the circuit is carried forward in other ways. Here again the conditions in practice are fairly varied, but it will suffice to indicate and illustrate the nature of the problems if we consider two cases.

The simplest case is that of a single-core cable which may be sealed by sweating the conductor solid into a thimble and wrapping the exposed dielectric with insulating and waterproof tape, as in making a joint. It is very important that the seal should be such that moisture cannot enter either between the stranded wires of the conductor or attack the dielectric if the latter be of fibrous material, such as paper. Even with other dielectrics great skill and care has to be exercised to obtain a satisfactory result. Examples of the sealing of rubber and bitumen cables have been given in Fig. 1.221.

With paper cables more elaborate devices have been found to be desirable, and one of these, a "sealing cap" designed by Messrs. Glover and Co., is shown in Fig. 1.238, fixed to the end of a lead-sheathed single-core paper cable; the left-hand half of the figure is partly in section. The objects to be attained are (*a*) to provide conducting connection from the copper of the cable to the terminal T, (*b*) to seal up effectively the dielectric and exposed copper strands, so that no moisture may reach either, and (*c*) to insulate the earthed lead sheath S S of the cable from T. The base of the cap is a heavy lead ring *b b*, shaped as shown, which can be slipped over the lead of the cable, beaten down on to it, and made quite watertight by the wiped plumber's joint *w w*. On this base, with a rubber [illegible] *r r* interposed, rests the corrugated p[illegible] projecting into the cup so formed is cut to len[illegible] in the usual way. The conductor is joined to [illegible] screwed [illegible] bolt *t t* by a convenient mechanical joint [illegible] an insulating compound, the usual pre[illegible] is closed by a metal cap *k k*, which is [illegible] a rubber washer being interposed. By the [illegible] is effectively sealed.



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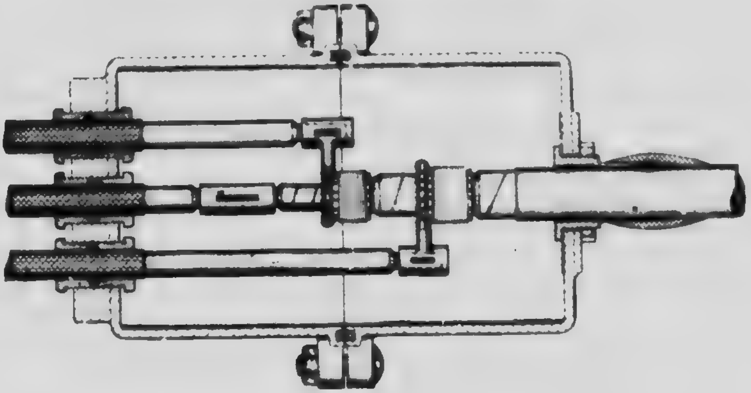

F[illegible]

Glover's Pa[illegible] Cable [illegible] B[illegible]

The disadvantage of such sealing caps, which are sometimes [illegible] "potheads," is the space which they occupy, an important point [illegible] have to be placed in feeder pillars or other places where space [illegible] The over-all size, for instance, for this particular cap for a cable with a conductor 1 square inch in area, is $4\frac{3}{8}$ inches diameter by $7\frac{1}{2}$ [illegible]

The second case selected is that of a terminal box for a triple [illegible] centric cable whose conductors are to be continued forward by three single-core cables. The design of such a box or "cable head," as [illegible] times called, depends upon whether it is to be used in the [illegible] vertical position. The box shown in elevation and plan in Fig[illegible]

1,240 is for use in the horizontal position. The main cable comes in on the right through a sweating gland, which can be made watertight in the way already described by a wiped plumber's joint with the lead of the cable. It is held in place by a screwed flange, as shown. The various layers of the cable are telescopically bared and trimmed in the usual way and the copper conductors are connected to the coppers of the tailing cables by convenient mechanical fittings, some details of which are shown. The copper ends of the ring conductors, it may be noted, are carefully bound with thin binding wires. The box is in two right and left halves which are eventually bolted together with a bitumen-cord packing ring to make the joints tight. The left-hand half carries the three exits for the tailing cables, which pass through stuffing bushes fixed in the end of the box, which is considerably thickened to receive them. Each bush is in two parts, which slip on to the cable, are screwed into the box end, and are made tight by bitumen-ring packing between them. When everything is in place and the box closed up insulating compound is filled in through one of the holes *h h*, the other being used as a vent, the usual precautions being observed. When the box is quite full the holes are closed by the screw plugs.

Earthing Metallic Sheaths. In certain services, notably in all mining work, it is necessary, and even compulsory, that the metallic sheath of a power-transmission cable shall be earthed by connection to an efficient earthing system. If properly effected this is the best safeguard that can be provided against electric shock. The metallic sheath referred to may either be the watertight lead sheath drawn over paper-insulated cables or protective armour, and the requirement is that this sheath shall, in all its parts, be properly connected to a good earthing system. The carrying out of this requirement necessitates (i.) that the sheath itself shall be electrically continuous throughout the whole length of the run of the cable, and (ii.) the provision of a good earth.

The first condition is satisfied by all parts of either type of cable which remain as originally manufactured, but there *may* be a break of continuity wherever there is a joint, and all joints must therefore be carefully designed with this requirement in view.

Bonding of Joints.—The requisite metallic connection of the sheaths on either side of a joint is amply secured with *lead-covered* cables by the instruction (*see* page 1176) that the lead sheaths are to be made water tight at the joint by what is known as a plumber's "wiped" joint, the usual watertight junction of lead pipes in all plumbing work.

With *armoured* cables the bonding together of the disconnected sheaths is not so easy, and requires some care. An excellent method is to clamp close up to the joint, a well-fitting cone connector on to the armour, the wires of which have been first carefully cleaned. The cone connectors on either side of the joint are then connected by stout metal straps of sufficient current-carrying capacity. Examples of this method have been given in the descriptions and illustrations of joint boxes, especially in Figs. 1,230, 1,231, 1,234, 1,235, and 1,237. In mining work it is specified that the conductivity of the armour shall not be less than 50 per cent. of the largest current-carrying conductor enclosed, and this must also apply to the conductivity of the joints, which should be periodically tested for conductivity to detect deterioration.

A good and interesting example of work in progress [illegible] recently completed for the making and bonding of tee joints on two concentric high-voltage cables is given in Fig. 1,241, which the reader is recommended to examine carefully.

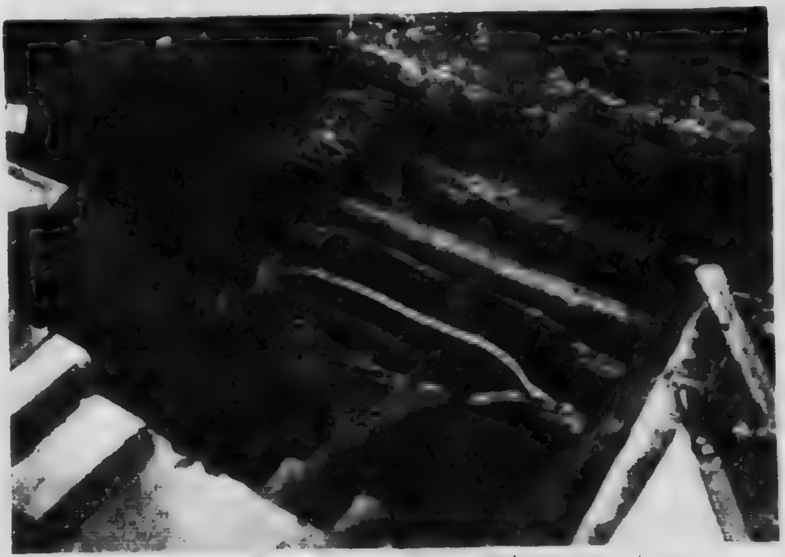

Fig. 1,241.—Bo[illegible] Joints on High-voltage [illegible]

Earthing System. This usually consists of plates of copper, cast iron or galvanised iron, sunk in earth which is either permanently wet or at least damp. These "earth plates," as they are called, are fixed upright and preferably surrounded with about 12 inches of broken [illegible] sulphur. Two plates, some 20 or 30 feet apart, well placed and electrically connected, are regarded as about twice as efficient as a single plate [illegible] a surface area equal to the two. In fact, the Board of Trade [illegible] under the Tramways Acts require *two* earth plates to be provided and periodically tested as follows: "The earth connections [illegible] shall be constructed, laid, and maintained so as to secure electrical contact w the general mass of earth, and so that, if possible, an E.M.F. not exceeding four volts shall suffice to produce a current of at least two amperes from one earth connection to the other through the earth, and a test shall be made once in every month to ascertain whether this requirement is complied with."

As to the size of the plates there is some conflict of expert opinion. The Home Office requires them to be "not less than 4 feet square," but Mr. A. P. Trotter, as a result of careful experiments, considers that a cast-iron plate 18 inches square is the best size. Such a plate, $\frac{1}{2}$ inch thick, allows a good bond to be made. The connections to the earth plates must be made by properly protected conductors, and no fuse, switch, or circuit breaker is allowed to be placed in such a connection or in an earth conductor.

Electrolysis Troubles.—The effective earthing of the sheaths is an important factor in minimising electrolysis troubles due to leakage currents of various kinds. This subject, however, will be more conveniently dealt with in the chapter on Electric Traction (*see* pages 1381 *et seq.*).

VI.—SYSTEMS OF TRANSMISSION

An elementary description, brief but fairly exhaustive, of the various practical systems, as distinct from methods of transmission, has been given in Vol. I. (*see* pages 576 to 582). These systems may, for our present purpose, be conveniently summarised here as follows, it being borne in mind that we are dealing with long-distance transmission at voltages so high that some method of stepping-down is required at the consumer's end to bring the voltage within the limits allowed for ordinary utilisation :—

(A) **Continuous-current Systems.**
    Two-wire, with transforming sub-stations in series.

(B) **Alternate-current Systems.**
    (*a*) Single-phase, two-wire.
    (*b*) Two-phase.
        (i.) Four-wire.
        (ii.) Three-wire.
    (*c*) Three-phase.
        (i.) Three-wire, star or delta (i.e. "mesh") connections.
        (ii.) Four-wire, star connections.
    (*d*) Polycyclic.
        Three-wire, single, and three-phase.

The subdivisions under (B) will probably be well understood by our readers, but reference may be made as to "star" and "delta" (i.e. "mesh") connections to Figs. 531 and 532 (page 553) in Vol. I. For transmission purposes with alternate-currents the secondary of a "step-up" transformer will frequently take the place of the generator so far as "line" connections are concerned, and at the distributing end the primary of a "step-down" transformer will almost invariably take the place of the "load." It may, however, be further explained that in (B) (*c*) (ii.) the fourth wire connects the neutral points of the star connections at the two ends of the line; also that in (B) (*b*) (ii.) the four wires of (*b*) (i.) are reduced to three by using one wire as a common return for the two phases. The polycyclic system will be referred to again presently. Historical notes on the development of the main systems will be found in Vol. I. (*loc. cit.*).

Engineering Efficiency.—The engineering efficiency of any system of transmission can only be ascertained by taking into account all the factors and circumstances, usually a very difficult matter, but the main items bearing upon the problem are—

(α) The conductor efficiency.
(β) Repairs and depreciation.
(γ) Maintenance, including working charges for attendance, etc.
(δ) Interest on capital expenditure.

Conductor Efficiency.—The term "efficiency," as applied to the conducting wires in electric transmission problems, is employed in the usual engineering sense to denote the ratio of the "output" of the electrical power or energy at the utilisation end of the line to the "input" of the electrical power or energy at the generator end. From what has been explained elsewhere it will be realised that theoretically this efficiency may be made to approximate closely to unity (or 100 per cent.) by diminishing the current on the line, and by lowering the resistance. The former means high voltage if large quantities of power have to be handled, whilst the latter tends to heavy capital expenditure in the material of the conductor employed and its erection or laying. In fact, the theoretical considerations being quite simple, the question to be answered with reference to any particular solution is the one which always confronts the engineer as distinguished from the scientist, namely:—"How can it be made to pay?"

Without losing sight of the fact that the cost of the conductor is far from being the total cost of laying out and equipping a transmission line, it will be convenient, in the first instance, to examine, quite simply, how this cost affects the problem of the transmission of a given amount of electrical power over a given distance. For clearness we take first the case of *two-wire transmission*, whether C.C. or A.C., but in the latter case we assume a power-factor of unity. Dealing only with the main factors, we know that for a *given amount* of power to be transmitted

$$\text{Current} \propto \frac{1}{\text{Voltage}},$$

and that for a *given weight of conducting material* used

$$\text{Resistance} \propto (\text{Length})^2$$

If, therefore, we arrange that the *voltage* shall be *proportional to the length of the line*, we see at once that for a given amount of power to be transmitted a given weight of conductor leads always to the same electrical efficiency, since the transmission loss (C^2R) is constant. It therefore remains only to discover in a given case the actual relation between the efficiency and the distance of transmission as determined by the known values and constants. With copper conductors, and with reasonable assumptions as to the ordinary price of copper, say £83 per ton, and the amount to be allowed as interest on its cost, say 6 per cent. per annum, the result comes out as

$$\frac{100 - x}{x} = \cdot00745\,L^2$$

where L is the length of the conductor in miles and x the percentage efficiency, the energy delivered being 1 kilowatt at 1,000 volts for one year, and the load-factor 100 per cent. Now take this result and apply it to a two-wire circuit, and, the distance of transmission being therefore ½L, we get the following table:—

TABLE XVIII.—CONDUCTOR EFFICIENCY FOR POWER DELIVERED AT 1,000 VOLTS.

Distance of Transmission.	Length of Circuit. (two-wire)	Percentage Efficiency.
1½ miles	3 miles	93·7
2 ,,	4 ,,	89·5
2½ ,,	5 ,,	84·3
3 ,,	6 ,,	78·9

This table shows how rapidly the efficiency falls off as the distance increases, the same weight of copper being used for each distance. It also gives some idea of the voltage to be used for long-distance transmission to secure high electrical efficiency. For instance, if the distance be 150 miles, a voltage of 100,000 must be used to secure a conductor efficiency of 93·7 per cent.

The efficiencies given in the table are, of course, for the particular case and for the particular assumed values of the quantities, but they may be accepted as showing in a general sense, and within not very wide limits, the obtainable efficiencies, in most cases, of long-distance transmission, whatever conductor be used or whatever reasonable assumptions be made regarding the value of capital and the cost of energy. Thus the general result is that if reasonable efficiency is to be attained over long distances, high voltages, ranging up to six figures, must be employed. The use of these high voltages introduces quite new factors into the problem, to many of which reference has been made in the preceding sections dealing with *methods* of transmission.

In the above calculations the conditions were simplified as much as possible, and the result is for a two-wire transmission of a given amount of power. No distinction was made between A.C. and C.C. transmission, but for the high voltages indicated, account must be taken in A.C. working of the fact that the maximum voltage upon which the breakdown of the dielectric depends is, for the simplest wave-form of current, $\sqrt{2}$ (=1·41) times the R.M.S. value of the voltage adopted. In comparing the different systems for equal *safety of insulation* as well as for *equal efficiency of transmission*, the weight of copper required will vary as the square of the pressure to earth. Introducing this additional factor and restricting the above calculation to the C.C. case, the *comparative weights* of copper required in the other chief cases will be as follows:

		Cwts.
Continuous current	(2 wires)	10
Alternating current,	*single-phase* (2 wires)	20
,, ,,	*three-phase* (3 wires)	15
,, ,,	*two-phase* (4 wires)	20
,, ,,	*two-phase* (3 wires)	29

If, however, certain parts of the systems are deliberately earthed, a proceeding which requires, as we may find space to develop later, other matters to be taken into consideration, the relative amounts of copper are considerably reduced. The following results are given by Mr. Brew * for the cases in which the maximum voltages to earth are the same:

		Cwts.
Continuous currents	(2 wires, one earthed)	10
Alternating currents	(*single-phase*, 2 wires, one earthed) . .	20
,, ,,	(*three-phase*, 3 wires, neutral point, earthed) .	5
,, ,,	(*two-phase*, 4 wires, one earthed) . .	20
,, ,,	(*two-phase*, 3 wires, common wire earthed)	14·6

Power-factors of A.C. Loads.—In the results just given it is assumed that the load at the distributing end of the line has unity power-factor. If, however, the load has a lower power-factor, the line will have to transmit the idle currents as well as the working current, and the $C^2 R$ loss for these currents must be taken into account. If the power-factor of the load be very low these losses may seriously alter the conductor efficiency of transmission, but whether the power-factor be high or low, they must be taken into account, and in comparison with C.C. transmission it must be remembered that in the latter the whole of the line current is a "working" current.

Other Expenditure.—It has been mentioned on page 1185 that the losses in the conductor are not the only factors to be taken into account by the engineer in deciding the system to be adopted in a given case. This was recognised clearly in the early days of the transmission of electric power, and a first approximation was embodied in a formula first put forward by Lord Kelvin and known as *Kelvin's law*, which may be stated as follows :—

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* "Three-phase Transmission," p. 174 (1911)

> *Maximum economy is attained in the transmission of a given amount of energy at a given voltage at the utilisation end of the line when the annual cost of the C^2R loss in the line is equal to the annual interest and depreciation charges on that part of the line, the cost of which varies with the sectional area of the conductors.*

To apply the law, even as thus given, it is obvious that the load-factor and, in A.C. systems, the power-factor must be taken into account. A low load-factor will mean decreased C^2R annual losses, whilst the annual interest and depreciation charges remain practically constant. On the other hand, these charges will be increased by a low power-factor requiring additional plant to produce the energy lost, for a low power-factor will increase the C^2R losses for a given amount of power transmitted. Whilst, therefore, it is a useful guide, Kelvin's law must be applied carefully and with a clear knowledge of its limitations.

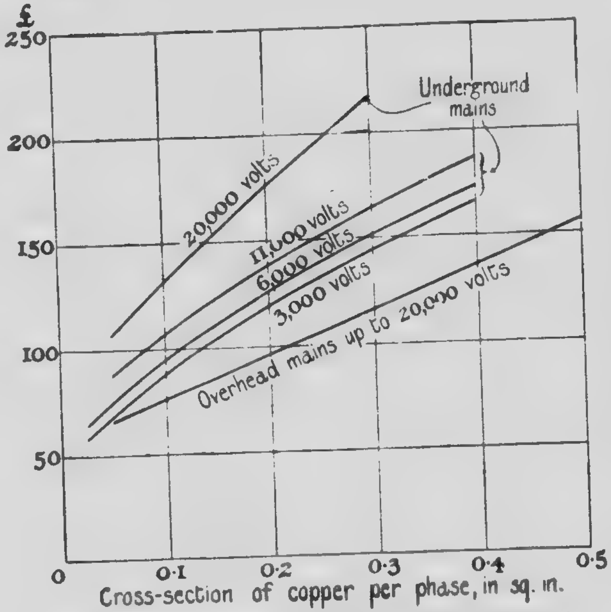

Fig. 1,242.—Annual Cost per Mile (Interest and Depreciation) of Three-phase Mains.

The curves in Figs. 1,242 and 1,243 give interesting comparative details of the effect of the method of transmission and the voltage on the annual charges for a three-phase system of transmission at moderate voltages. They are taken from a paper* by Mr. J. C. Beard. In Fig. 1,242 the abscissæ are the cross-section of the copper conductor in square inches, in each of the three phases, and the ordinates the annual charge per mile of line for interest on capital and for depreciation. Curves are given for overhead mains at 20,000 volts, and for underground mains for four voltages from 3,000 to 20,000 volts. Interest on capital has been taken at 5 per cent. and depreciation at 2 per cent. for underground and 3 per cent. for overhead mains. The latter figures probably underestimate the life of the mains, but in these matters it is well to adopt conservative estimates, and there has not, as yet, been time for experience to evolve reliable figures for modern systems. The results are full of interest. For instance, for copper of 0·2 square inch at 20,000 volts the charge for overhead mains is about £95 per mile per annum, whilst for underground mains at the same voltage the charge is about £175. The charge for underground mains at substantially lower voltages is less, but it must be borne in mind that the power transmitted will also be less for the same conductor efficiency of transmission.

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* *Journal of the Institution of Electrical Engineers*, Vol. LIV. p. 125 (1916)

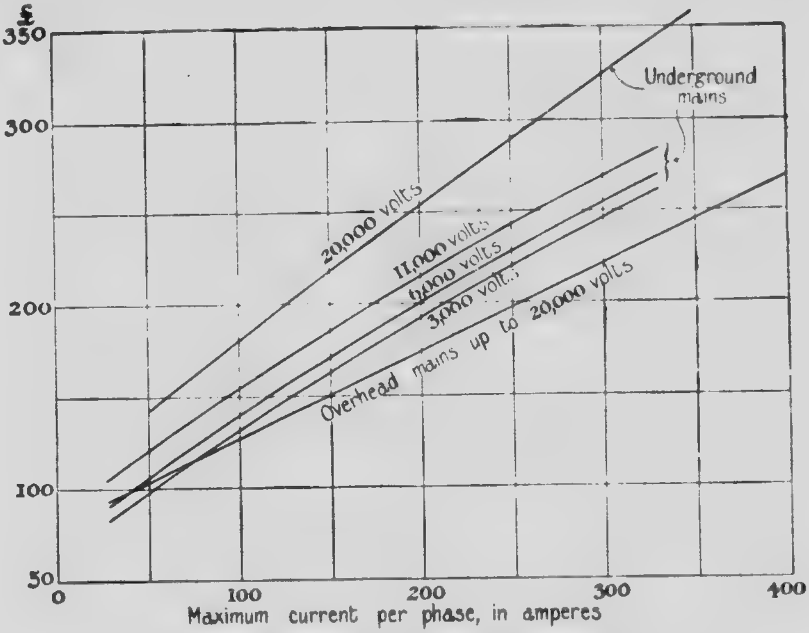

Fig. 1,243.—Minimum Total Annual Cost per Mile (Interest and Depreciation) for Three-phase Mains Designed for various Maximum Currents.

In Fig. 1,243 the details are carried a step further by the inclusion in the ordinates of an allowance for repairs based upon records obtained from actual systems. The abscissæ are also changed by substituting the maximum current per phase for the cross section of the copper, the most economical sections of copper being chosen for each current. This brings the curves closer together, and gives the minimum total annual cost per mile for the different currents. It may be noted that at 150 amperes per phase the annual charge, including repairs for the overhead mains, is £150 per mile per annum against £220 for underground mains, the voltage being 20,000 in each case. Other interesting curves, including the influence of the power-factor, are given in the paper, which is well worth consulting.

Continuous-current Systems.—The foregoing pages contain details of actual high-voltage transmission lines, whether overhead or underground, and whether the currents used are continuous or alternating. Other matters of general interest—such as the efficiency of transmission, costs of erection, etc.—have also been dealt with. Generators, motors, transformers, etc., of all kinds, without which actual transmission of electric energy would be impossible or useless, have been fully described. With one exception detailed descriptions of actual systems as a whole would therefore appear to be unnecessary, especially as the special subject of "protective gear," because of its importance, is taken separately later on.

There are, however, certain matters connected with high-voltage continuous-current generation and transmission to which little reference has yet been made, and which are most conveniently dealt with by a brief description with illustrations drawn from the successful but relatively few examples in which this system of transmission is utilised.

The only method of obtaining, by continuous-current generators, high voltages comparable with those used in alternate-current transmission, is by arranging a battery of dynamos in series with one another (*see* pages 387 *et seq.*) instead of running them in parallel as is more usual. In series the same current passes through each machine, which is therefore designed for *constant current* instead of for the constant voltage of parallel running. The current being constant, the load must be varied by varying the voltage, and the methods of switching machines in and out for this purpose are described, in principle, in the earlier section referred to.

As early as 1889 a small continuous-current installation, transmitting electric power 7·6 miles at 14,000 volts, was installed in Italy, and was followed by other installations at voltages varying from 6,800 to 14,000 in Switzerland, Italy, Spain, and elsewhere. It was not till 1902 that the line voltage was raised to 27,000 volts in the St. Maurice-Lausanne transmission.

A much greater project than any of its forerunners was inaugurated in 1906 by M. Thury for the transmission of electric power with continuous currents from Moutiers to Lyons, a distance of 112 miles, using a voltage of 57,600 volts on the line, which consisted of 106 miles of overhead wire and 6 miles of underground cable. Additional generating stations were added at La Bridoire and Bozel in 1911 and 1912, and the line voltage raised to 75,000 volts. In this country the system was adopted by Mr. J. S. Highfield for the western area of the Metropolitan Electric Supply

Company, where, however, it is rather a question of ***distribution*** at high voltage than of ***transmission***, as the farthest sub-station supplied is only seven miles from the generating station.

The highest voltage that, as yet, can be obtained from a single high-power continuous-current generator is about 5,000 volts, and a Dick Kerr dynamo giving this voltage, and controlled by a Thury regulator, is described at page 195 (Fig. 192). To obtain the line voltages referred to above, it is therefore necessary to connect the generators in series, which, in its turn, makes it necessary to insulate the separate machines from one another and from the prime movers driving them. The general plan is shown diagrammatically at the top part of Fig. 1,244.* in which three 4,000-volt dynamos are shown in series, giving a line pressure of 12,000 volts. The output of the three machines is 2,400 kilowatts, which can be transmitted with a line current of only 200 amperes. This current is kept constant at all loads, the load being varied by varying the voltage. The line current, as shown in the lower part of the diagram, is passed in series through motors of various sizes which are built for varying voltages, but all carrying the same current of 200 amperes. Thus a 100-kilowatt motor takes 500 volts, a 200-kilowatt machine 1,000 volts, and so on. These motors, where not used directly for mechanical work, drive suitable C.C. or A.C. generators for supplying the electrical needs of the neighbourhood of the sub-station in which they are placed.

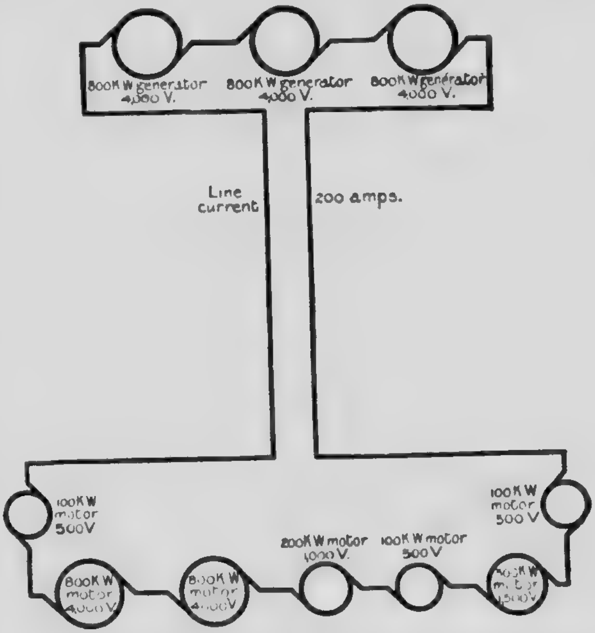

Fig. 1,244.—Diagram of a High-voltage Continuous-current System.

The switching arrangements, either for generator or motor, are quite simple; they are shown diagrammatically in Fig. 1,245, in which C and D are the main generator and motor switches respectively. For small variations of load the voltage of the generators is controlled by a Thury regulator (*see* Fig. 191, page 195), but when the load falls so far that a generator can be removed from the circuit, its removal is brought about not by disconnecting it, but by *short-circuiting* its armature and field-magnets, after which it can be stopped or not, as may be convenient. In cases of emergency, this short-circuiting can be done automatically by suitably designed switches (B and F in Fig. 1,245). Similarly, a motor can be put out of action by short-circuiting, and in the diagram of Fig. 1,245 the switches C and D are both shown in the short-circuiting position. To place the machines in circuit each switch should have its movable contacts rotated 90°.

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* This and some of the following figures are taken from papers by Mr. J. S. Highfield, read before the *Institution of Electrical Engineers.*

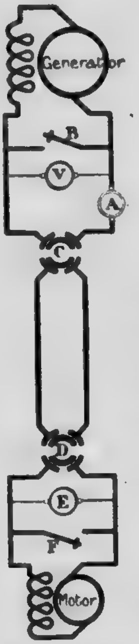

Fig. 1,245.—Diagram of Switching Arrangements on a High-voltage c.c. System.

An actual switch pillar with its instruments is shown in Fig. 1,246, the connections to generator or motor and line being indicated diagrammatically. A side view, partly in section, is given in Fig. 1,247. Four fixed cylindric segments, with mid-points 90° apart, are connected to the line and generator, thus forming together the two line terminals on the one hand and the two dynamo terminals on the other. The movable contacts are much wider cylindric segments mounted on corrugated porcelain insulators so as to be concentric with the fixed contacts. They are operated by a carefully insulated handle which has only two positions, "on" and "off," 90° apart. For working as shown in the figure, the movable contacts connect the two right-hand and the two left-hand fixed contacts. In the "off" position the two lower and the two upper fixed contacts are connected, thus short-circuiting the dynamo armature, as explained above, and putting the line "through" without drawing energy from it.

In the Moutiers station as originally equipped by M. Thury there were sixteen 3,600-volt dynamos in series arranged in four groups of four machines, each group being driven by a single water turbine the speed of which was controlled by a regulator, set to keep the current constant at all loads. The dynamos were in pairs, each pair being on a shaft with an insulating coupling between the machines. A view of the station, which is of historical as well as of present-day interest, is given in Fig. 1,248,* reproduced from a photograph taken soon after its first opening. The rotor of each machine has an output of 270 kilowatts when developing its full voltage of 3,600 volts. The mounting

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*From the *Electrical Review*, Vol. LIX., p. 219 (1906).

of two dynamos on a single bedplate is shown in greater detail in Fig. 1,249.

The combined voltage of each set of four dynamos was therefore 14,400 volts at full load, and the P.D. between the + and — lines 57,600 volts. As, however, the mid-point of the battery was earthed,

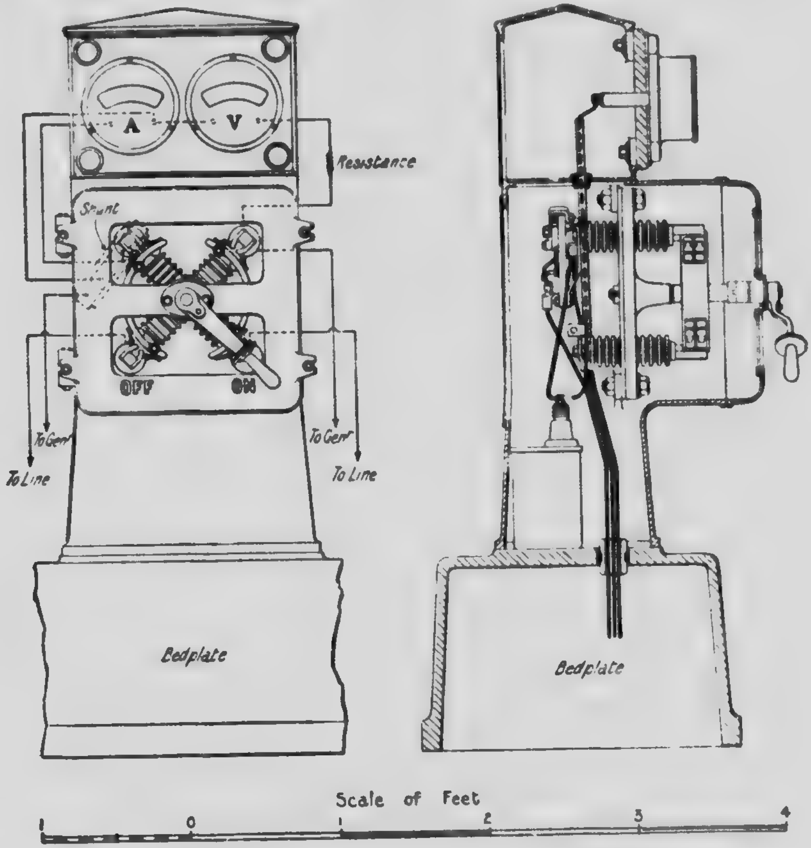

Fig. 1,246. Fig. 1,247.

Switch Pillar with Instruments.

the P.D. to earth was nowhere greater than 28,800 volts. The current being kept constant at 75 amperes, the full-load output was 4,320 kilowatts or 1,080 kilowatts for each shaft at full load. The interconnections of the machines are shown diagrammatically in Fig. 1,250, in which are also shown the connections to the transmission lines and the distant load. The arrangements for earthing the mid-potential point of the system are also indicated by dotted lines, and it will be observed that the machines can be thrown on and off in pairs, as mounted on their bed-plates. The device of altering the P.D. of each machine by shifting the brushes was not used in the generating station, but in the sub-stations. In the generating station the P.D. for small variations of load was adjusted by electrical regulation of the speed of the water turbines until the point was reached at which machines ought to be switched on on rising loads or short circuited on falling loads. The switching pillars were similar to those illustrated in Fig. 1,246, but of an earlier type.

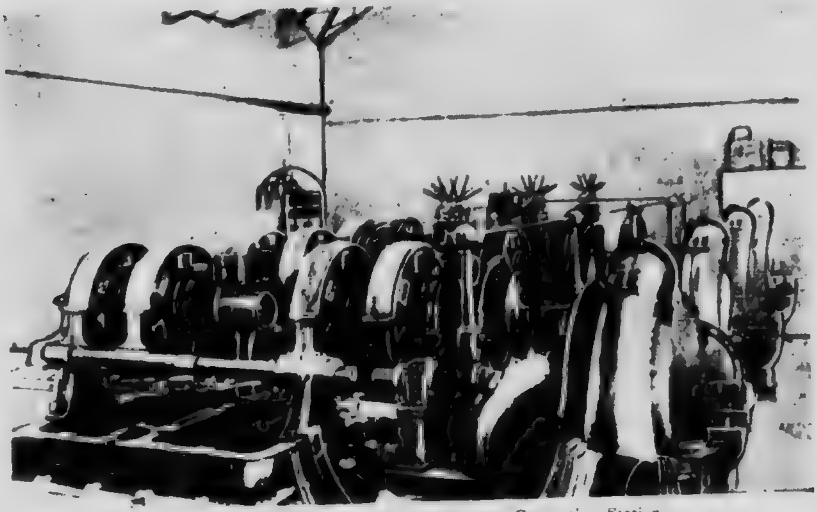

Fig. 1,248.—The Moutiers High-voltage C.C. Generating Station.

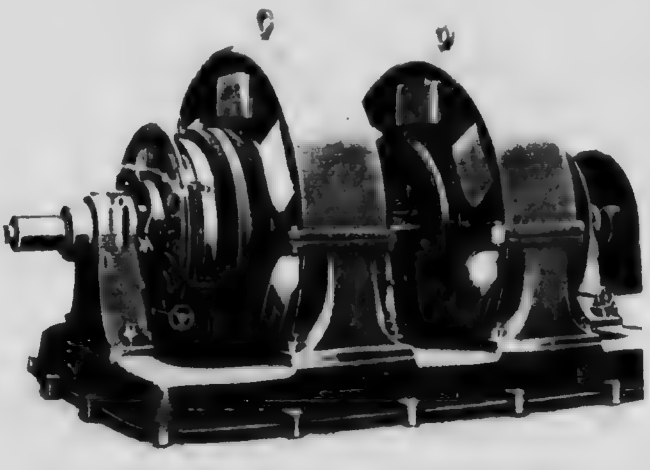

Fig. 1,249.—Two Coupled 3,600-volt C.C. Dynamos.

It is obvious that one of the elements of success of such a system lies in careful attention to the details of insulation. Mention has already been made of the insulating couplings between the two armature shafts on the same bedplate, and, of course, similar couplings were placed between the shafts on the two bedplates in each set, and between the machines and the driving turbine. But to prevent leakage to other machines it was necessary to insulate the bedplates, and this was accomplished by supporting the bedplates (*see* Fig. 1,248) on double-cup insulators by means of bolts passing through the lugs (*see* Fig. 1,249) round the bottom of the bedplate. As a further precaution the floor of the power-room was made of insulating materials. On a continuous bed of concrete covering the whole room there was placed a layer, $1\frac{1}{2}$ cms. thick, of asphalt mixed with small stones, and on the top of this, forming the working surface of the floor, a layer of pure asphalt more than a centimetre in thickness. These layers of asphalt placed upon a continuous bed of concrete tend to insulate the generating station, and if the room be kept warm and dry render it difficult for even the bed-plates to become "dead-earthed" in the ordinary sense of the term.

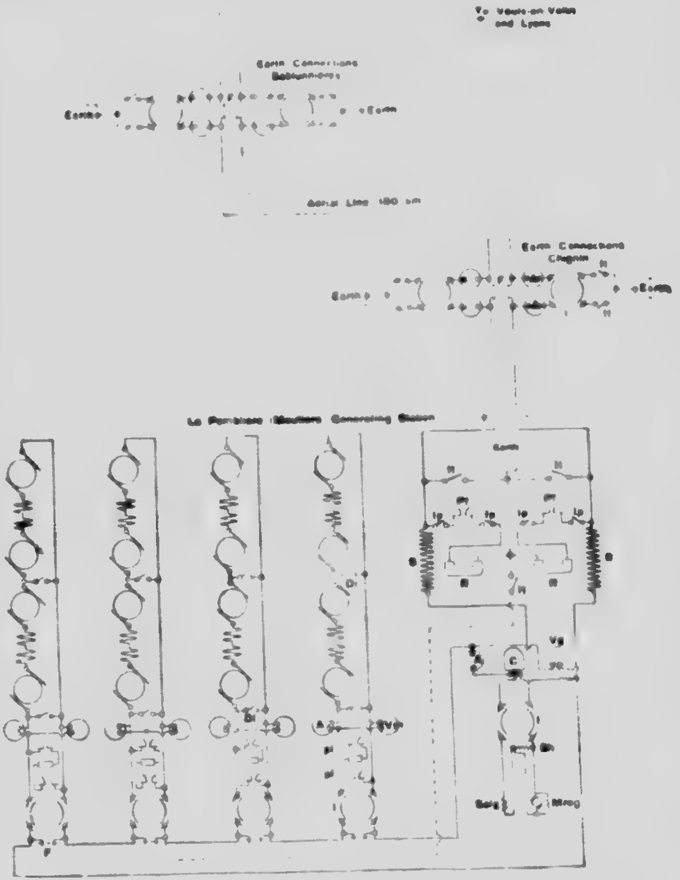

Fig. 1,25 .—Diagrams of Connections of Thury c.c. High-voltage Syst

Alternate-current Systems.—So many details of alternate-current working have been given in the preceding pages that the mere summary of systems on page 1184 is almost sufficient for our purpose. Moreover, various questions bearing on the relative advantages of the different systems enumerated have been discussed incidentally, *e.g.* the relative advantages of single and polyphase motors.

Obviously, as a matter of mere transmission, the single-phase system with its two wires as against the three or more wires of polyphase systems scores a point as regards first cost and upkeep, an advantage which it shares with high-voltage continuous-current systems.

There are, however, in alternate-current working one or two outstanding matters bearing specially on transmission which have not as yet been touched upon and which are most conveniently taken up at this stage.

Ferranti Effect.—One characteristic in which A.C. differs from C.C. transmission is in the existence in the former of an A.C. reactance voltage due to the electrical properties of the transmission line itself. This leads sometimes to very curious and interesting results, such as the voltage at the far or distributing end of the line being higher than at the near or generator end. This effect was first observed in the Ferranti main laid down in 1889 for the 10,000-volt transmission from Deptford to Bond Street, in London, and is therefore frequently referred to as the *Ferranti effect* or the *Ferranti phenomenon.* The distance in this historic case was about 6 miles, the cables were concentric, paper-insulated cables, and each mile had a capacity of 0·367 microfarad, an inductance of ·280 millihenry, a resistance of 0·324 ohm, and an insulation resistance of 700 megohms. The periodicity was 85 ∽.

The effect is due to the phase relations of the quantities involved, for, as our readers are fully aware, a rise of pressure at a point supplied with A.C. energy does not necessarily mean an increase in the power delivered at that point. The phenomenon was investigated in 1890 by Professor Fleming, Sir William Preece, and others in a series of experiments in which two cables, each 10,112 yards long, were looped together at the London end so that the two ends of the loop at Deptford could be used, one for delivering energy to the cable and the other for receiving it after transmission through about twelve miles of cable. This enabled the necessary measurements at the two ends to be made in the same building.

The experiments are too extensive to be described in detail, [illegible] results can be briefly summarised. A step-up (1 : 4) transformer was used at the generator or home end, and a similar step-down (4 : 1) transformer at the receiving or far end. It was found (*a*) that the high-voltage pressure at the far end of the mains was always less than that at the near end when the far end secondary circuit was loaded, and that (*b*) with this secondary circuit unloaded the pressure at the far end of the mains was higher than that at the near end. In a particular [illegible] 7,240 volts delivered to the mains at the home end became [illegible] at the far end, the only load being the high-voltage coil of the transformer which, as the secondary circuit was open or [illegible] act [illegible] simply as an inductance or choking coil.

The arrangement of mains and transformers [illegible] ally in Fig. 1,251, in which G is the generator [illegible] transformers respectively, A A the insulated [illegible] outer main, the two lengths of cable being joined [illegible] D [illegible] electrical connections are approximately [illegible] however [illegible] diagram Fig. 1,252, in which [illegible] capacity of the [illegible] was bridged across the terminals P_1, P_2 [illegible] the receiving transformer T_2, which is only approximately correct, as the capacity is distributed along the whole length of the cable.

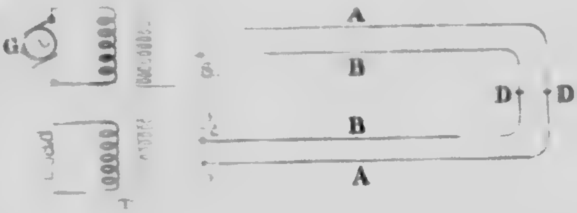

Fig. 1,251. [illegible] of Connections for Test on the "Ferranti Effect"

The results specified, were all the data available, could be approximately [illegible] by the principles [illegible] set forth elsewhere in this book. Unfortunately the inductance of the coil (Fig. 1,252) of the far-end [illegible] and is [illegible] given and therefore we must use vector diagrams which [illegible] the results are possible. The diagrams are given in Figs. 1,253 and 1,254. The first figure (1,253) shows the currents C_1 and C_2 in [illegible] to be joined in parallel across the terminals P_1 and P_2, the potential difference ($P_1 - P_2$) between which is represented by the vertical vector P_1 P_2. The condenser current C_1 *leads* 90° on the voltage $P_1 - P_2$, whilst the coil current C_2 lags nearly 90°, being the magnetising current in the transformer. The current C_1 may be much larger than the current C_2, and [illegible] delivered by the mains to the terminals will be the vector [illegible] and C_2 which, because of the angle C_2OC_1 being very obtuse, [illegible] than C_1, the condenser current. The second figure (1,254) shows [illegible] C and $P_1 - P_2$ in the same positions, with the additional vector S_1 [illegible] P_1, the potential difference between the two ends of [illegible] (Fig. 1,252). The angle at O between the vectors C and $S_1 - P_1$ [illegible] approximately correct according to the data given, which show that [illegible] inductive reactance (pL) at 85 ∿ is 1·8 ohms, the ohmic resistance being 3·9 ohms. The value OS of this P.D., which is relatively much exaggerated in the figure, combined with OV_1 the value of $P_1 - P_2$, gives the vector OV_2, which is the P.D. ($S_1 - P_2$) or ($S_1 - S_2$), the voltage deliv-

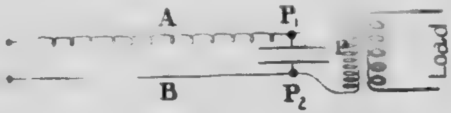

Fig. 1,252. [illegible] Approximate Electrical Conditions of the Test ered to the line at the home end. As the angle $o\,v_2\,v_1$ is greater than the angle $o\,v_1\,v_2$, it follows that $o\,v_1$ is greater than $o\,v_2$, that is, the voltage across the transformer terminals $P_1\,P_2$ is greater than the voltage $(S_1 - S_2)$ delivered to the mains at the home end.

It is thus seen that the Ferranti effect, of which the above is only a general explanation, is quite in accordance with known laws, and is not, as was at first supposed by many, an indication of some previously undiscovered fundamental law. It is due mainly to phase-differences caused by reactance. The effect is not so great on overhead lines as on underground cables because of the lower electrostatic capacity, but it is very noticeable on long high-voltage transmission circuits. Thus, on the Big Creek to Los Angeles transmission line, which is 240 miles long, the delivery voltage at no-load is 10 per cent. higher than at the generating end. As the voltage of transmission is 150,000 volts this means a rise of 15,000 volts due to this effect.

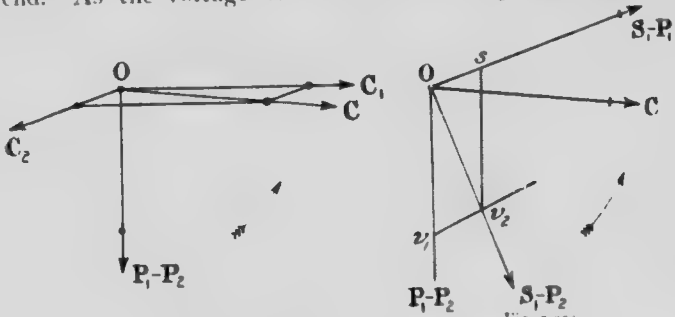

Fig. 1,253. Fig. 1,254.
Vector Diagrams for the "Ferranti Effect."

Other Reactance Effects.—In actual practice other important results follow from the same causes. These will be most simply illustrated by considering the Ferranti mains in Fig. 1,252 with the transformer T_2 removed. In that case we have a resistance R in *series* with a condenser, and the equations for the current between S_1 and S_2, and between P_1 and P_2 are (*see* Vol. I., page 548) :—

$$C = \frac{S_1 - S_2}{\sqrt{R^2 + \left(\frac{1}{p\,K} - p\,L\right)^2}} = \frac{P_1 - P_2}{\frac{1}{p\,K}}$$

where $R = 3{\cdot}9$ ohms, the resistance of the cable,

$L = 3{\cdot}4$ millihenries, the inductance of the cable,

$K = 4{\cdot}5$ microfarads, the capacity of the cable.

If we take the working frequency at 85 ∽, and therefore $p = 534$ $(85 \times 2\pi)$, these figures give—

the permissive reactance $= \dfrac{1}{p\,K} = 416$ ohms,

the inductive reactance $= p\,L = 1{\cdot}8$ ohms,

the total reactance $= \left(\dfrac{1}{p\,K} - p\,L\right) = 414{\cdot}2$ ohms.

The effect of inductance is to lower the reactance due to capacity, but in the above case the effect is so small as to be practically negligible.

If, however, the two reactances were equal to one another, that is, if L were 0·79 henry, $\frac{1}{p\text{K}} = p\text{L}$, the current would be given by the equation:

$$\text{C} = \frac{\text{S}_1 - \text{S}_2}{\text{R}}$$

$$= \frac{10000}{3{\cdot}9} = 2{,}560 \text{ amperes}$$

a very dangerous current, since the full-load current of the generator used in the experiments was about 250 amperes only, and this current was cut down by the step-up transformer. It may be admitted at once that for this extreme case a more rigorous method of calculation should be used, which need not be detailed here; but the result shows the kind of physical effect to be anticipated if the inductance of a circuit cancels the capacity.

The cancellation of the inductive reactance by the permissive reactance can be effected in either of two theoretically simple ways: (i.) by lengthening the cable, and (ii.) by increasing the periodicity. As regards (i.) a simple calculation shows that if the above cable were 183 miles long each reactance would be about 28 ohms, and they would therefore cancel one another. The result would be a heavy and dangerous charging current of the order shown in the above equation.

The effect of change of periodicity in bringing about much the same result would occur without altering the length of the line at such a periodicity as would make the two reactances equal. Calculation shows that this periodicity is 1,286 ∽, at which each reactance again becomes about 28 ohms. The actual periodicity is 85 ∽, and is fixed by the speed of the generator. It is quite obvious that this speed cannot be increased fifteen times, but this does not dispose of the danger, as we shall now show.

Resonance.—The phenomena which are manifested when the periodicity is such that the reactance due to inductance is cancelled by the reactance due to capacity is frequently referred to as electrical "resonance," from certain analogies with acoustical "resonance" in the science of sound. The circuit behaves as a stretched string tuned to respond to a particular fundamental note or any of its simple harmonics. The lagging wave of inductive E.M.F. cancels the leading wave charging the condenser, and leaves the line to behave as if it had neither inductance nor capacity. The amplitude in this case of the wave of current due to a particular alternating E.M.F. is therefore enormously increased, and is determined by the ohmic resistance only.

The fact that resonance can occur at the periodicities of the simple harmonics or overtones, as well as for the periodicity of the fundamental wave, must not be overlooked, for, as we have shown elsewhere (*see* page 342 *et seq.*), such harmonics, more particularly those of an odd order (third, fifth, seventh, etc.) are present in most commercial alternating current waves. For instance, in the Ferranti cable it has just been shown that resonance may be expected with the working periodicity of 85 ∿ if the cable be 183 miles long. Similar calculations show that the cable will respond to the third harmonic if it be sixty-one miles long, to the fifth harmonic if it be twenty-seven miles long, and so on.

With the actual cable resonance occurs with a periodicity of 1,286 ∿, which is very nearly fifteen times the fundamental periodicity of 85 ∿, and if the fundamental periodicity rose to nearly 85¾ the fifteenth harmonic would have the required periodicity. This rise of periodicity would be effected by a rise of less than 1 per cent. in the speed of the engine. If therefore there happened to be a pronounced fifteenth harmonic in the voltage wave, there would be danger of resonance effects by small changes of engine speed. The remedy is obvious. A small inductance put in series with the line would destroy the balance which makes the fifteenth harmonic dangerous; but care would have to be exercised that the particular choking coil used did not bring into prominence other harmonics which are present. Another remedy is to work, if possible, with simple sine-waves in which there are no harmonics.

Three-phase Connections.—As a final contribution to outstanding matters in connection with alternate-current transmission, a brief reference may be made to the two chief methods of connecting up the phases in three-phase circuits. The fact that step-up and step-down transformers used for transmission purposes may have either circuit "star" or "delta" connected, not to mention more complicated methods (*e.g.* Fig. 965), naturally raises the question as to whether either method has any outstanding advantage as compared with the other. As a matter of mere permutations, it is obvious that there are sixteen different ways in which two transformers and a three-wire transmission line may be joined up without the additional cases which would be possible if a fourth line wire might also be used. The transformer at either end may also be either a single three-phase transformer, or may consist of three similar single-phase transformers suitably connected.

It has already been shown (*see* page 942) that for all voltages the star method of connection, for a given P.D. between the terminals, leads to smaller stresses on the insulating material, and therefore to a decreased capital cost for a similar factor of safety. This is more especially the case if the neutral point can be earthed.

On the other hand, the consequences of the difference in wave form between the magnetic flux and the magnetising currents shown in Fig. 950 cannot be overlooked. The case there referred to is the wave form of the current required to produce a simple sine-wave of flux, and therefore a simple sine-wave of induced E.M.F. in the electric circuits. Elsewhere it is shown that all distortions from the simple sine-wave form can be traced to the presence of harmonics, and in this case the effect is chiefly produced by the presence of a pronounced third and of less important higher harmonics in the magnetising current due to the hysteresis loop of the transformer iron. It is easy to see that, *vice versa*, if this third harmonic is absent from the magnetising current there will be a third harmonic in the wave-form of the magnetic flux, and therefore in the wave forms of the induced E.M.F.S.

The presence of these third harmonics in the system may give rise to added difficulties in switching operations and when short circuits or earths occur, a subject which is dealt with elsewhere; and therefore if by the method of connection these difficulties can be reduced or eliminated the point should be borne in mind, though it may not be, in itself, decisive. Now the delta method of connections affords a closed circuit of low impedance to the flow of currents caused by third harmonic P.D.S between lines, whereas no such circuit is afforded by the star method of connection.

Another advantage of the delta method of connection appears when three single-phase transformers are so connected and one of them breaks down or fails. The two sound transformers in this event are still able to supply three-phase power, only at a diminished rating; the supply need not be interrupted, all that is necessary being to cut out the defective transformer.

It is not possible in the space available, to consider the effects due to these peculiarities in all their details. To sum up, it may be said that when single-phase transformers are used the advantages of the star-star connection lies in its simplicity and lower capital cost, whereas the delta-delta connection has the advantage of greater flexibility and the absence of the third harmonic in the P.D.S between the lines, with the disadvantage, however, of higher stresses on the insulating material of the transformers. The other two solutions of star-delta or delta-star for high- and low-voltage circuits respectively lead to other considerations which have led to much controversy. The advantages and disadvantages are accentuated in the high-voltage (100 kilovolts and over) transmission systems, of which there are now numerous successful examples, which may be held to embody the results of experience. Examining these, it is found that in America the majority of these high-voltage systems use delta-star step-up transformers and star-delta step-down transformers, the transmission lines being thus at both ends joined up to star-connected circuits in the transformers, the low voltage circuits of which at each end are delta connected. For transmission systems at lower voltages, say 50,000 volts and under, the high-voltage transformer windings may be either star or delta connected, the chief advantage of the delta connection being its greater flexibility.

Ring Mains.—When in an important transmission scheme the chief distributing sub-stations and large consumers are conveniently situated, it is desirable to run the transmission lines so that they eventually form a loop returning to the generating station, when the conductors at the end of the loop can be again connected to the busbars, etc., of the main switchboard. Such a system is known as a "ring-main" system, and can be applied on either continuous or alternate-current systems. In fact, when the transmission line is very long and there is practically only one chief distributing centre, it is customary to divide the line into two lines ordinarily worked in parallel, but which may be regarded as constituting the limiting case of the ring-main idea.

The outstanding advantage is that the supply can be maintained at all the distributing points, even though a serious fault should occur at one point of the ring circuits. Even when a supply is required by a large consumer it is found usually better to run the transmission line from the nearest available ring main, though the consumer's works are situated some distance therefrom, rather than give him separate mains from the generating station.

To obtain the best results from the method, the protective gear and switch arrangements at each of the transforming sub-stations have to be carefully designed.

Continuous *v.* Alternate-current Transmission.—The outstanding advantages of continuous-current over alternate-current transmission lie (i.) in the absence of inductive and capacity effects, and therefore in always working with unity power factor with no losses due to idle currents; and (ii.) in the working voltage from which the power is calculated being the voltage which determines the breaking down of the insulation, whether by disruption or corona effects, instead of this being determined by a much higher voltage, the peak voltage of the wave. Moreover, there is with alternate currents the increased loss due to the "skin" effect wherever conductors of large cross section or currents of high periodicity have to be employed. Per contra, there are now available more or less effective methods for improving the power factor. These matters are fully discussed elsewhere.

The disadvantages under which continuous-current transmission suffers in comparison with its rivals is the much greater difficulty of obtaining the highest voltages which are now in quite common use for alternate-current transmission. In other words, in continuous-current working there is no engineering apparatus corresponding in its working range to the step-up static transformer.

On the other hand, it is claimed for the high-voltage continuous-current series system of transmission :—

(i.) That, especially where underground cable transmission is essential, it is more flexible, and the economical distance of transmission can be extended beyond that possible with alternate currents.

(ii.) That the switch gear and regulating gear is simpler and easier to manipulate.

(iii.) That the uniform section of the mains allows additional loads to be accepted and provided for by the installation of new stations at any convenient point on the route of the mains, these new stations being run in simple series with the original station.

(iv.) That this running of stations or plant in series simplifies the problem of dealing with peak loads, and gives a more efficient solution than is possible with alternate currents.

(v.) That the speed regulation of motor-generators in the sub-stations for special loads is more efficient.

(vi.) That greater overall efficiency is obtained when the generators are driven by turbines operated by water with great variations of head.

Polycyclic Transmission.—This method of transmission is based upon the independence of two alternate currents of different frequency, or, in the limiting case, of an alternate and a continuous current when flowing along the same conductor. Such systems were worked out and experimented upon in 1902 by Arnold and La Cour in Germany and by Bedell in America. Since that time they have been revived more than once as offering, under certain conditions, a solution of the problems involved in supplying efficiently from the same circuits lighting and power plants, in view of the fact that a high frequency is better for glow-lamp and arc-lamp lighting, and a low frequency for alternate-current motors.

The subject is very interesting, and it was originally intended to describe briefly and with suitable diagrams the devices for overcoming the various practical difficulties which arise. The method, however, has not, so far as the author is aware, ever been developed on a large scale, and therefore, in view of the pressure on our space for other matters of more immediate practical interest, it has been decided to insert only this brief reference to what may possibly be worked out more fully in the future.

VII.—SYSTEMS OF DISTRIBUTION

Pressure Permitted.—In systems of distribution of electric power as distinct from systems of transmission the outstanding feature is that, except in special cases, quite a moderate voltage has to be employed, since the apparatus has to be handled by non-technical consumers who, to safeguard possibly fatal consequences, must not be liable to the dangers of contact with exposed parts of circuits of even moderately high voltage.

In fact, most of the regulations for the public supply of electric power, including lighting, to the ordinary consumer limit the pressure which may be used to 250 volts above earth potential, which is defined as the voltage of a "*low-pressure supply*," or to 650 volts for special purposes, this being defined as a "*medium pressure supply*," only permitted when certain extra precautions are observed. In English Board of Trade regulations when the pressure is over 650 volts up to 3,000 the supply is "deemed a *high-pressure supply*," and above 3,000 volts it is "deemed an *extra high-pressure supply*," and these pressures are not allowed in a "supply delivered to any consumers."

Systems in Use.—The systems in common use at the present time for distributing electric power from a generating or a sub-station to consumers may be summarised as follows:—

(A) **Continuous-current Systems.**
- (*a*) Two-wire systems giving a direct supply at "low pressure."
- (*b*) Three-wire systems giving a direct supply (i.) at "low-pressure" between the adjacent conductors, and (ii.) at "medium pressure" between the outer conductors for special purposes.
- (*c*) Two-wire systems giving a direct supply at "medium pressure" for traction.

(B) **Alternate-current Systems.**
- (*a*) Two-wire systems giving a single-phase supply at "low pressure."
- (*b*) Three-wire systems giving from two-phase transformers (i.) single-phase supply at "low pressure" between either phase and the neutral conductor, and (ii.) two-phase supply at "medium pressure" between phases.
- (*c*) Three- or four-wire three-phase systems giving (i.) "a low pressure" single-phase supply between phases or between a phase and the neutral conductor, and (ii.) a three-phase supply for power purposes at "medium pressure."

The low voltage permitted, 650 volts or under, leads to continuous currents being far more commonly used in distributing systems than in transmission systems, not only because of the absence of the capacity, inductive and other effects referred to in preceding pages, but also because the consumer's apparatus is either better adapted to utilise continuous-current power or is equally well adapted for either type. There is, as we have seen also, no special difficulty either in generating continuous-current power at 650 volts and under or in transforming to such power from high-voltage transmission mains. Thus it has come to pass that whilst by far the greater part of the world's supply of electric power is generated as alternate-current power, the actual final utilisation of such power for industrial and domestic purposes is widely in the form of continuous-current power.

In the early days of the distribution of publicly supplied electric power more complicated systems were used in addition to those above scheduled. For instance, both in Paris and Vienna "five-wire" systems of distribution were laid down, and descriptions of these and of the balancers and other apparatus required will be found in the early editions of this book. In this as in some other, but not in all, directions modern developments have tended towards greater simplicity. A five-wire balancer as being still of historical interest will be found described in Vol. I. (*see* page 635) of this edition.

Distributors.—The object of the distribution being usually to supply numerous consumers in a limited area with electric power at low pressure, it is most frequently more convenient to use underground rather than overhead methods of running the conductors. In what follows, except other methods are specially referred to, it will be assumed that underground cables are used and that one or other of the systems described earlier in this chapter is adopted for laying the cables.

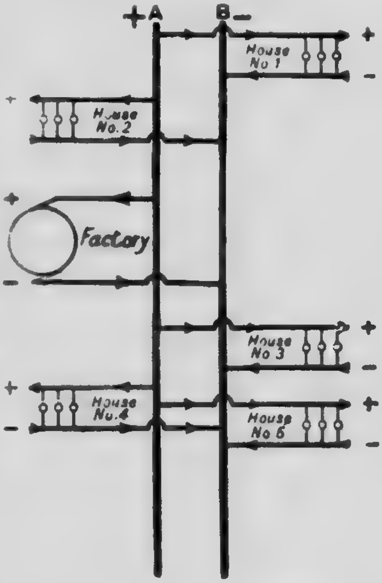

Fig. 1.255.—Two-wire Distribution.

Two-wire Distribution.—In low-pressure distribution of electric energy, whether by continuous or alternate currents, the simplest system is one in which two insulated conductors are used. The different consumers are connected, electrically in parallel, to these two conductors, and in practice each consumer is given a pair of terminals, one connected to each conductor, to which, through suitable safety and measuring apparatus and switches, his utilisation devices—lamps, motors, furnaces, etc. etc.—are connected. In view of all that has already appeared, it is scarcely necessary to give a diagram of these simple connections, but for completeness one is given in Fig. 1.255, in which the course of the distributors down a short length of street containing ordinary dwelling-houses and a factory is diagrammatically sketched. This sketch, which covers the cases A (*a*) and B (*a*) on page 1204, needs no comment except, perhaps, that the symbols + and — imply continuous-current working, whereas the sketch will serve just as well for alternate currents. The voltage between the mains is kept constant, the main A in continuous-current working being the "+" and the main B the "—" conductor.

Three-wire Distribution.—In these systems, which, as already mentioned, are the modern survivors of more complicated systems, electric energy of either kind is supplied at "low" pressure to ordinary consumers for lighting and domestic purposes generally, whilst consumers of electric energy for "power" purposes are supplied at double the pressure, thus obtaining a "medium" pressure supply, the maximum pressure being, however, only 500 volts.

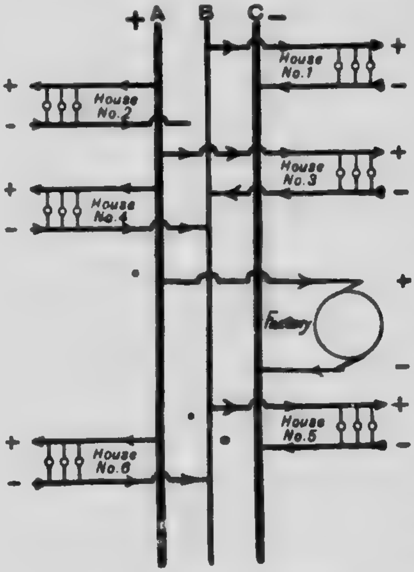

Fig. 1,256.—Three-wire Distribution.

The system consists in running three wires instead of two. Two of these wires, known as the "outers," are of full cross section for the maximum current load to be carried, whilst the third, known as the "neutral" or "middle" wire, is, in modern practice, of half or one-third this cross section. Cables specially designed for such distribution will be found illustrated in cross section in Figs. 1,186, 1,187, and 1,188 on page 1143.

The method itself for a short length of the route is illustrated diagrammatically in Fig. 1,256. The mains A and C, the "outers," are maintained at a constant P.D., of not exceeding 500 volts, which is within the range of "medium-pressure supply," and which is double the P.D. of not exceeding 250 volts, the highest pressure allowed to be supplied to any ordinary domestic consumer. The supply leads for such consumers are connected *either* to A and B, *or* to B and C, but *not* to A and C. On the other hand, in the "factory" where special protective devices can be installed and where probably there is some degree of skilled supervision, connection is given to mains A and C at the full P.D. of 500 volts, which, in the diagram, is represented as being supplied to an electric motor for transforming the electrical into mechanical power.

Networks.—In any given district with numerous consumers in different streets and in different directions from the generating or the sub-station, it is obvious that if all possible customers are to be supplied an elaborate system of distributing mains must be laid down. The most convenient location for the underground cables is under the footwalks, where they can usually be laid, and be made accessible with the least disturbance of heavy traffic. In important thoroughfares these distributing mains are laid on both sides of the street, but in less important streets one set of mains may be used to supply houses on both sides, though this must mean disturbing the roadway when some of the connections are being made.

It is obvious that mains so laid in any ordinary urban or suburban district must form a network closely following the plan of the principal streets and cross streets, and may be regarded electrically as a development of the "ring-main" plan referred to on page 1202, inasmuch as any particular point on the network can be reached by more than one route from the source of current. Part of such a *two-wire* network is depicted diagrammatically in the fine lines in Fig. 1,257, and it is obvious that if any accident happens within the network area bounded by the Figure Y, Z, T, S, U, W, X—for instance, at the point T—the faulty section may be cut out of circuit without interfering with the supply to any consumers except those directly connected to the piece cut out. Some parts of the distributing system are, it will be noticed, represented as being outside the network area, and therefore lose this advantage.

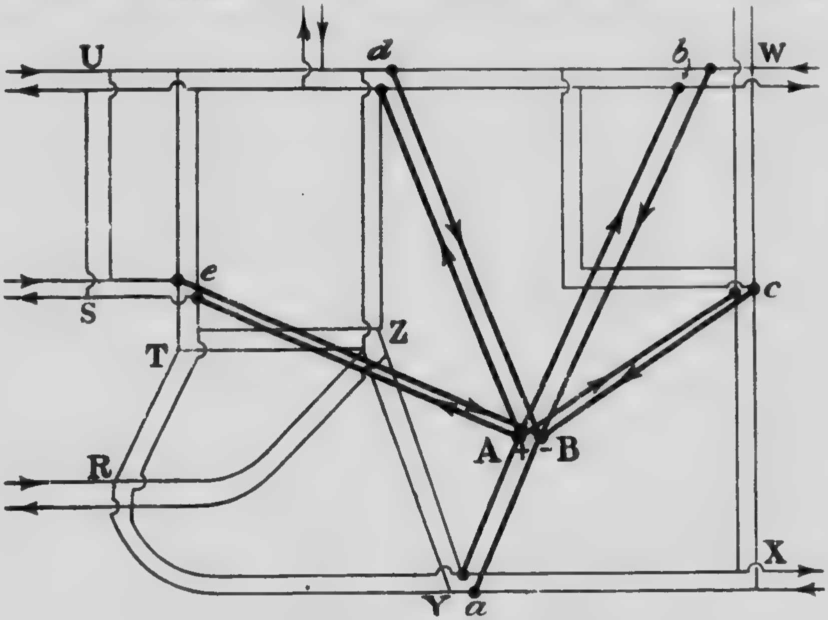

Fig. 1,257.—Simple Case of a Two-wire Network, showing Feeders.

The arrangement of a *three-wire* network is similar to that sketched in Fig. 1,257, and does not call for a separate figure. The fine lines of the sketch may be taken to represent the "outers," and since the "neutral" wire would usually, in this case, be contained in the same cable, the ground plan of the wiring would remain unchanged.

Feeders.—In modern working the low- and medium-pressure electric energy is usually supplied from a sub-station situated within the area, and drawing its supply of energy from the high-pressure transmission lines referred to in the last section. The outgoing terminals of such a sub-station are represented by the dots A and B in Fig. 1,257, of which A is the $+^{ve}$ and B the $-^{ve}$ terminal. If the network were connected to A and B only by the distributors just referred to, it is obvious that because of the $(C^2 \times R)$ loss of voltage caused by the ohmic resistance of the conductors the consumers in distant parts of the network would receive a lower voltage than those near A B. Worse still, this voltage, if the P.D. at A B were kept constant, as it should be, would fluctuate, becoming greater when the load on the network and consequently the loss of voltage was light, and dropping as the load increased. As certain consuming devices—for instance, glow lamps—are very sensitive to such changes of pressure, dissatisfaction and complaints would arise if the changes were allowed to occur.

Instead, therefore, of connecting the distributing network directly to A and B, special mains are run from A B to carefully selected points *a*, *b*, *c*, *d* and *e* on the network, and by certain devices to which reference is made in the chapter on sub-stations, the P.D.s at these points are kept approximately constant. These extra mains are known as "feeders," and are indicated in Fig. 1,257 by the thick lines running from A and B to the "feeding points." From such points there are led back thin insulated wires, called "pilot" wires, which, when connected to the voltmeters at the station, enable the attendant to ascertain the P.D. at the feeding points, and thus show him when it is necessary to take steps to keep the pressure constant. These pilot wires are shown in the cross-section of the cable illustrated in Fig. 1,200.

In a three-wire system the feeders, which theoretically need only be cables containing two wires, would be attached to the "outers" of the distributors, and thus for a given low-pressure load on the distributors would carry only one-half the current required for the same load at the same pressure in a two-wire system, hence leading to the saving in copper which is one of the chief reasons for using the three-wire system in lieu of the two-wire one.

The use of two-wire feeders on a three-wire system would only be practically possible if the loads on the two sides of the system were perfectly balanced at all times. With the fluctuating loads due to the varied and varying loads of many consumers, this condition obviously cannot be satisfied, and therefore the feeder cable also usually contains a third or "neutral" of a cross section one-third to one-half of that of each of the "'outers." This enables the balancing arrangements, which are described in the next chapter, to be in the generating or sub-station under skilled supervision and practically continuous observation.

Calculation of Currents.—The first step in dealing with the problem of the sizes of the conductors to be laid down for a given distribution system is to obtain some idea, however approximate, of the maximum currents they will have to carry. In this connection the student should re-read the remarks made on pages 420 to 432 on "Load Curves," on "Load Factors," and on "Diversity Factors." Many of these remarks are relevant to the present problem, but need not be repeated here.

The complexity of the problem will be further realised by considering the easier problem of calculating the currents in the network depicted in Fig. 1,257, assuming fixed loads and that the resistances of the conductors are known. The calculation can be made most readily by the application of the generalisation of the laws of current flow and Ohm's law, fully explained in Vol. I., and usually referred to as Kirchhoff's laws, because they were first stated in this form by Kirchhoff. These laws are specially useful in all network calculations, and we therefore give them here, merely premising that if currents *towards* a point are reckoned as +", those flowing *from* a point must be reckoned as —' and *vice versa* :—

(i.) *The algebraic sum of the currents which meet at any point is zero.*

(ii.) *In any closed circuit the algebraic sum of the products of the current in and the resistance of each conductor or part of a conductor of the circuit is equal to the* E.M.F. *in the circuit.*

The calculation can be shortened by certain devices, which would take too much space to explain in detail here, but which will be found in books dealing fully with the subject. When so shortened, however, the numerical work is laborious, even for the very simple case of Fig. 1,257, but the results *can* be obtained and are quite definite ; in fact, machines have been invented for lightening the drudgery of the numerical calculations.

Our present problem, whilst of the same nature, is more complex and does not admit of an exact numerical solution without the expenditure of a disproportionate amount of time in intricate computations. It is to determine the most economical resistances to adopt for each conductor of the network. These could be ascertained exactly for a given distribution of a fixed load, but in view of the varying load curves referred to above and the diversity factors of different consumers the *load is not fixed* but is fluctuating in different ways at every load point of the network, and therefore the problem of accurately determining the most economical size of the mains is *in practice* insoluble. This does not mean, however, that no calculation should be made, or that the sizes should be chosen haphazard. Some attempt should be made to determine the maximum currents in each conductor of the network, and then the problem of the sizes of the mains can be separately considered as set forth below. The current values adopted will necessarily be quite approximate, but some hints as to methods of approximation may be given.

C.C. Circuits.—The maximum current in the simple case of a definite maximum C.C. load supplied through *two-wire* distributors is easily obtained from first principles by the equation—

$$\text{Maximum current} = \frac{\text{maximum load in watts}}{\text{voltage of supply}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For a *three-wire* C.C. distribution this will also give the current in the outers, and it is usually assumed that the current in the neutral wire will never exceed one-third of the current in the outers, even when the two sides are much out of balance.

A.C. Circuits.—In the case of *single-phase* distribution with two-wire or three-wire distributors, the power-factor of the load must not be overlooked; equation (1) must now be written—

$$\text{Maximum current} = \frac{\text{maximum load in watts}}{\text{voltage of supply} \times \text{power factor}} \quad . \quad . \quad . \quad . \quad (2)$$

In other respects the calculations are the same as for continuous currents.

In the case of *two-phase* distribution, if *four wires* are used each phase may be assumed to take half of a balanced load, and with this modification the calculation is the same as for single-phase distribution. If the load be not balanced the increase due to possible "out-of-balance" currents must be allowed for. If *three wires* only are used—that is, if one wire is a common return—the current in that wire must be taken as 1·41 times the current in the outers, and the cross section increased accordingly.

For *three-phase* three-wire distribution the maximum current in each wire on a balanced load is given by the equation—

$$\text{Maximum current} = \frac{\text{maximum load in watts}}{1{\cdot}73 \times \text{voltage between phases} \times \text{power factor}} \quad . \quad (3)$$

Increased current due to out-of-balance working must be provided for. In this case it is well to use four wires, the fourth or neutral wire being designed to carry one-half to full current of the outers according to the degree of out-of-balance working expected. In A.C. circuits, should large conductors be necessary, the "*Skin Effect,*" which increases the ohmic resistance, especially at high periodicities, must not be overlooked. Tables giving numerical values for this increase will be found in works of reference.

Sizes of Cables and Conductors.—The maximum current to be carried by a conductor fixes approximately within certain limits the size or cross-section of the conductor to be laid down. Other factors bearing on the problem, such as the minimum thickness of insulation, etc., have been standardised and tabulated as explained later. As compared with the similar problem in a transmission scheme (see page 1188), the chief differences are the low voltages used and the shortness of the distances involved, both of which bring into prominence factors which may be ignored in long-distance transmissions. The feeder problems are intermediate between the network problems and those for long-distance transmissions.

There is, however, one factor in transmission problems which disappears from distribution problems—namely, that which takes account of the voltage at which the insulation breaks down. The maximum voltages used in distribution are fixed by considerations of safeguarding the personal safety of the consumers, and are so low that for any practical case the rupture of the insulation need not be considered.

Having, therefore, obtained a maximum value of the current to be carried, the size of the conductor to be used can be ascertained by one of three methods, namely—

(*a*) By assuming that a certain maximum current density is permissible irrespective of the size of the conductor.

(*b*) By allowing a certain drop in volts at full load.

(*c*) By ensuring that the temperature rise of the cable, at full load long continued, shall not endanger the insulating properties of the insulator with regard to which a proper factor of safety is allowed.

The first (*a*) of these methods is crude, but has the merit of simplicity. With those who use it a current density of 1,000 amperes per square inch may be said to be quite fashionable. It is an easy density to remember and use. Thus 100 amperes would require one-tenth of a square inch of copper, 268 amperes 0·268 of a square inch, and so on.

The method, however, is scientifically absurd and indefensible, considered from the point of view of the dangerous heating of the wire. It is easy to see that with a fixed current density a thick wire will—other conditions being the same—be heated to a higher temperature than a thin one. For instance, compare the cases of two wires, one 0·01 square inch in cross section and the other 1·0 square inch. Under the 1,000-ampere rule the first will carry a current of 10 amperes and the second a current of 1,000 amperes, whilst the heat generated per second in the latter case will be 100 times that generated in the former. This heat accumulates and has to be got rid of by conduction and radiation, in both of [illegible] the area of the outer surface of the copper is an important and direct factor. But the second wire has only 10 times the surface of the first, and [illegible] upon to dissipate 100 times the heat. To effect this the temperature must be raised.

The fact is that, from the heating point of view, the rule is absurdly safe for all small insulated wires with standard thicknesses of insulation. It comes up to the standard practice of method (*c*), as explained below, at 150 amperes for rubber-covered cables, at 200 amperes for cables insulated with vulcanised bitumen, and at 700 amperes for paper or fibre-insulated cables. If the rule be adopted for larger currents respectively in these cables, the cables will be unduly heated under standard conditions.

Either method (*b*) or method (*c*) should therefore be adopted in the general case. As fully explained in the last section, the percentage drop in volts determines the conductor efficiency of transmission, and is the predominant factor in fixing the size of the conductor for long-distance working. The same may be said with regard to most feeders, especially long ones. In this connection it may be pointed out that the 1,000-ampere rule discussed above leads to a drop of 1 volt for each 20 yards run of double conductor (lead and return), whatever the voltage of distribution may be. Therefore, with low-voltage distribution an uneconomical drop is reached in a short distance. Thus, at the maximum voltage of 250 volts between the two wires, a drop of 1 per cent. is effected in 50 yards. The permissible drop in the I. E. E. rules* for lighting circuits "must not exceed 2 per cent. *plus* a constant allowance of 1 volt." This gives 6 volts as a maximum for low-pressure circuits (two-wire) and 11 volts on the outers for three-wire systems. The first limit is reached in 120 yards run and the second in 220 yards, or one-eighth of a mile. These distances are often exceeded in practice, and therefore the 1,000-ampere rule must be discarded and larger conductors used, the size being fixed by the permissible drop in volts if method (*b*) be used.

In method (*c*) a different set of considerations is involved. For each insulating material there is a temperature beyond which it should not be heated, lest its insulating properties should deteriorate. This temperature in the I. E. E. rules is assumed to be 54·4° C. (130° F.) for rubber and 80° C. (176° F.) for paper or fibre. It being then further assumed that the maximum temperature of the air will not exceed 37·7° C. (100° F.), the currents, determined experimentally which can be carried by various sizes of cables, are recorded so that the rise of temperature at full-current load shall not exceed 11·1° C. (20° F.) for rubber cables and 27·7° C. (50° F.) for paper or fibre-insulated cables. These results are embodied in a valuable table issued with the I. E. E. rules, which should be consulted in determining the sizes of distributors to be used.

One remark may be made in conclusion. The adoption of the most economical size for the conductors in each part of the network would necessitate the stocking of a great number of different sizes of cables, even if only the approximate determinations be adopted, and still more so if more accurate calculations are available. It is obviously of practical importance from many points of view that the number of sizes of cable used should be reduced to a minimum, and this consideration alone makes it unnecessary to carry the calculations referred to above to a high degree of accuracy.

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* *Wiring Rules of the Institution of Electrical Engineers*, 6th edn., issued April, 1911

Overhead *v.* Underground Transmission. The relative advantages and disadvantages of overhead and underground methods of transmission will have emerged in the foregoing pages, and it will have become evident that neither method holds the field to the exclusion of the other. The method to be adopted in a particular case will be decided, as in most engineering enterprises, by an expert weighing of the whole of the special conditions, oftentimes conflicting; and, above all, by keeping well in view the financial commitments and probable financial results. The special conditions will sometimes point decidedly to the use of overhead conductors and sometimes just as decidedly to the use of underground cables. The best possible solution will, as a rule, be a compromise in which favourable and adverse circumstances are most skilfully balanced against one another.

CHAPTER XII

SUB-STATIONS

As an indispensable link in any modern scheme for the electric transmission and distribution of power, even on a moderate scale, the sub-station plays a very important part, and should have as much care bestowed upon all details of its erection and equipment, including a careful choice of site, as the main generating station.

The function of a sub-station is to change the type or voltage, and even more frequently both the type and the voltage, of the electrical power, so that it may be suitable for the next step in the scheme. The necessity arises as regards type, because, as we have seen in the preceding pages, it has been found more advantageous to transmit electric power over long distances in the form of alternate electric currents, whilst for many industrial purposes the continuous-current type is the more convenient for final utilisation. As regards voltage, the most economical and possible voltages for long-distance transmission are much higher than can be, at present, directly generated, and are still further removed from the voltages which have been found both convenient and desirable for ordinary use whatever form of utilisation is required by the consumer.

A sub-station is therefore required, not only at the consumer's end of the transmission line, where most of the generated voltages are too high; but sometimes even at the generating end, so that the voltage generated may be "stepped up" to bring it to the level necessary for economical transmission.

In the preceding pages the various classes of electric power transforming apparatus have been fully described, and incidentally some details of sub-station work have already been given in connection with generating stations in Chapter III. The object of the present chapter is to describe how these and their accessories are assembled and co-ordinated to form an efficient and flexible link in the general scheme.

For clearness of arrangement we cannot do better than adopt the same divisions of the subject that have been adopted in describing the different types of transformers separately in Chapters VII., VIII., and IX., leaving for the present, since their modern form is now being evolved, "Rectifier" sub-stations already described briefly in Chapter X.

We shall therefore deal separately with :—

(*a*) Static transformer sub-stations.
(*b*) Kinetic transformer sub-stations.
(*c*) Secondary battery sub-stations ;

in which the voltages do not exceed, say, 30,000. The sub-stations—static transformers and chiefly outdoor—handling the highest voltages, 50 kilovolts and over, will be more conveniently dealt with in a separate section after (*a*). The above classification is convenient, but not exclusive, for it frequently happens, more especially in section [illegible], that more than one type of transformer is installed in a particular sub-station. A final section will be devoted to operations of general interest in sub-stations.

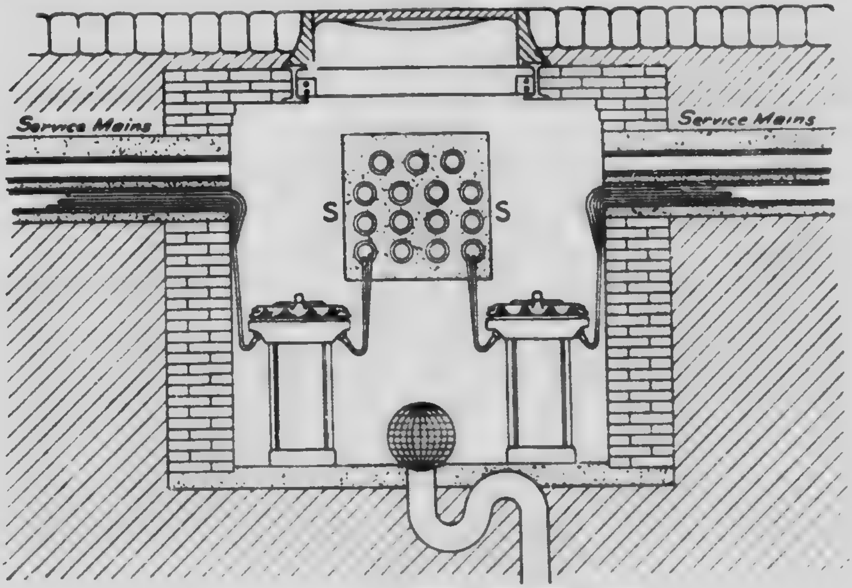

Fig. [illegible].—Section of a Subway Transformer Chamber.

I.—STATIC TRANSFORMER SUB-STATIONS

Wherever the power is supplied and has to be passed on in the alternate-current form with a mere change of voltage, or a change of voltage and phase, the proper type of transformer is the static transformer, which is the simplest of all transformers, as it has no moving parts and therefore requires a minimum of attention. In the early days of the alternate-current supply of electric power it was the custom to distribute from the generating station at a voltage higher than was permissible for general consumers' use, and a properly protected step-down parallel transformer or a series transformer was installed in or near the consumer's premises.

Only the secondary circuits of the transformer at a low and safe voltage were accessible to the consumer. The primary circuits of the transformer were always on the supply mains, and the open circuit losses, for which no charge could be made to the consumer, were sometimes considerable.

As experience increased, it was found much more economical to combine the transformers for a convenient group or set of consumers in a single transformer of less capacity than the sum of the capacities of the displaced transformers, and whose no-load losses would be less than the sum of the no-load losses of the separate subscribers' transformers. Part of the energy saved was, of course, lost in the higher C^2R losses of the secondary network; but on the whole, for obvious reasons, a substantial gain resulted.

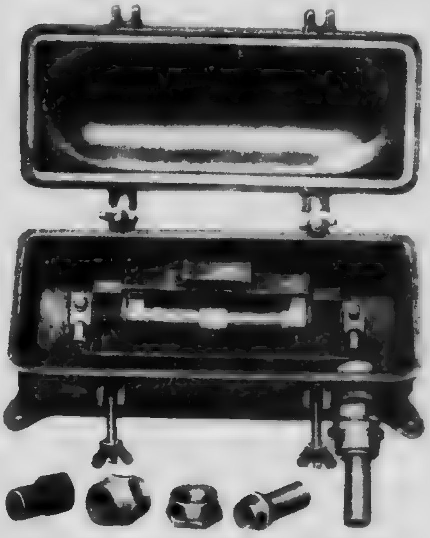

Fig. [illegible].—Fuse Box for a Subway Transformer Chamber

The transformer, or transformer for a group of subscribers is conveniently and cheaply accommodated in a chamber, usually brick-lined and excavated beneath the roadway or footway of a public thoroughfare; and thus has been evolved the simplest form of sub-station that could be devised, namely the "Subway Transformer Chamber." A section of a standard type of such a sub-station is given in Fig. 1,258, which depicts a subway transformer chamber as designed by the engineers of the General Electric Company of Schenectady. The section is almost self-explanatory. The high-voltage service mains, in ducts at a convenient distance below the roadway, enter the chamber at one side, and, if required, leave it at another, to pass on to other sub-stations. In passing through they supply the primary circuits of the two transformers shown, and any additional ones in the chamber. The secondary circuits are led away to the consumers through the ducts s s. The chamber should be made as watertight as possible, and closed at the top, with a manhole having a watertight cover. To provide against any accidental accumulation of water, the lowest point is connected through a properly trapped duct to the sewer as shown. The transformers also, as described elsewhere, should be in watertight cases with watertight bushings for the entry of the cables. Such standard subway transformers are made in sizes from 5 to 100 kilovolt-amperes. Their no-load losses should be as small as possible, their radiating surfaces large, and their temperature rise small at full load, since the chambers are usually unventilated and thermally almost insulated.

The only other apparatus that might be considered necessary in such a sub-station is a watertight fuse-box containing a suitable fuse. A standard pattern of such a box, as manufactured by the General Electric Company, is shown in Fig. 1,259. It can be attached to the walls of the chamber in any convenient position. The cover is provided with a moulded rubber gasket to render it watertight.

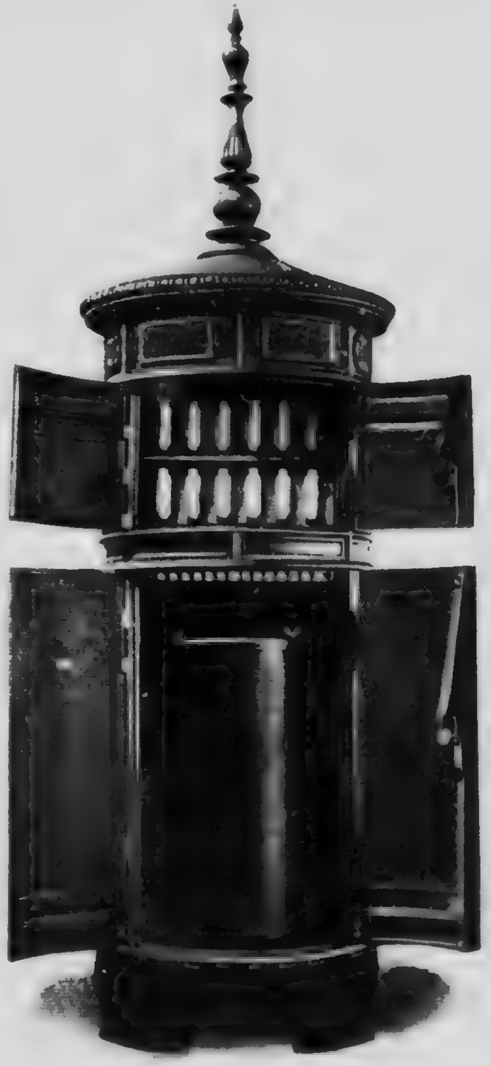

Fig. 1,260.—Kiosk Sub-station of the British Electric Transformer Co.

The transformer chamber need not necessarily be underground, but may be placed above the surface if care be taken in the design of the containing kiosk. Such a chamber of an ornamental character, designed by the British Electric Transformer Co., Limited, for use in residential districts, is shown in Fig. 1,260; it is surmounted by a lamp which, of course, receives energy from the transformer inside. The kiosk is divided horizontally into two chambers, an upper and a lower, and can be opened for inspection by folding-doors on opposite sides. The lower chamber contains the transformer, which may be of any required size up to 100 kilovolt-amperes for three-phase currents, or 150 kilovolt-amperes for single-phase. The upper chamber, which is the shallower, contains on one side the high-voltage fuses and on the other the low-voltage fuses. There is also space for some switch gear if deemed necessary. Both high-voltage and low-voltage leads are, of course, brought into the kiosk from underground conduits.

The simple subway chamber is of course unsuitable if the power to be dealt with is large, or if switching operations and measurements are necessary. It is also unsuitable if the primary voltage be much above 650 volts. The conditions being fairly simple, the design of a more substantial sub-station offers few difficulties when the conditions are properly realised. The subject of "Static Sub-station Design" was dealt with very fully by Mr. P. V. Hunter in a paper read before the Institution of Electrical Engineers in 1911,* and Figs. 1,261 to 1,264 are taken from that paper, in which as many as twelve different designs are described. The variations depend upon the number of transformers installed, the type of transformer, whether self or otherwise cooled, and the ventilating [illegible] arrangements, [illegible] the relative positions of switchgear and tran[illegible] the positions of high- and low-voltage switchgear relative to [illegible] accessibility of the transformer and the arrangements [illegible].

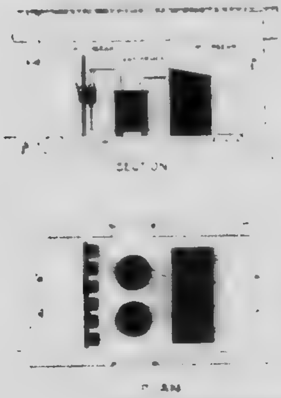

FIG. 1,261.—[illegible]

The simplest [illegible], that of two self-cooled transformers, is shown in section and in plan in Fig. 1,261. The transformers are placed between the two sets of switchgear, and the high-voltage [illegible] at the right-hand side pass [illegible] the station, and [illegible] low-voltage energy from the left-hand [illegible] arrangement is convenient [illegible] has the disadvantage that the switchboards are back to back, and therefore [illegible] in front of one board can[illegible] the other board.

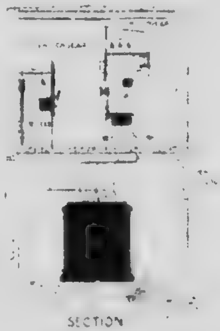

FIG. 1,262.—[illegible] Two-storey [illegible] Sub-station.

This disadvantage is removed [illegible] shown in Fig. 1,262, in which [illegible] two storeys, the transformers [illegible] the ground floor, and the switchboards, now facing one another [illegible] the upper room. The transformers are in separate [illegible] to diminish the fire risk; but very little provision [illegible] ventilation. The switchboards, both high and low voltage, [illegible] the respective switchboards. The oil and other switches are directly operated, and the low-voltage feeders are racked against the left-hand wall and leave the building at the end. This station was built in 1904.

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* *Journal of the Institution of Electrical Engineers*, [illegible] page [illegible].

A far more elaborate arrangement is shown in Figs. 1,263 and 1,264, which give the section and plan of a station dealing with a maximum load of 12,000 *kV.A.* in four sections of 3,000 *kV.A.* each. The transformers are oil-insulated and water-cooled by means of special coolers, which are placed in the lean-to at the left-hand side, the oil and the water being pumped through the transformers by pumps driven by alternate-current motors. The transformation is from 6,000 volts to 20,000 volts, the voltage being raised for trunk-line transmission. Only the high-voltage switch gear is indicated in the figures. Overhead lifting gear is provided in the transformer room, this being rendered necessary for the repair and overhauling of the transformers, each of which weighs upwards of 25 tons. Serious repairs are best carried out at a central rep-

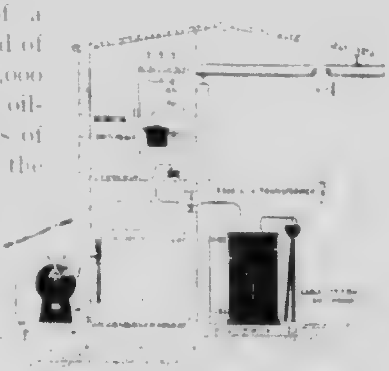

Fig. 1,263.—Section of 1[illegible]

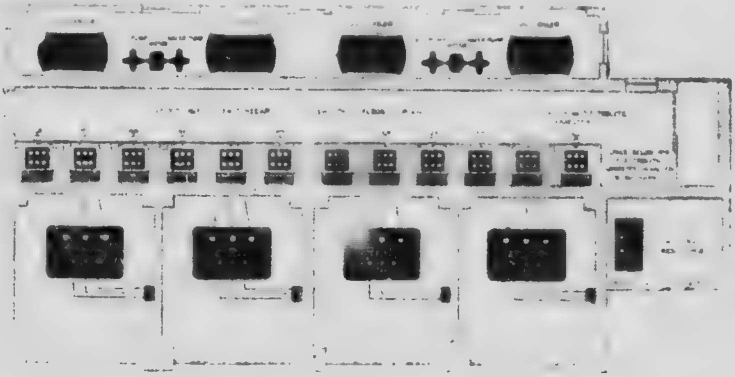

Fig. 1,264.—Plan of 12,000 kV.A. Transformer Sub-station with Oil and Water-cooled [illegible] P

[illegible] heavy transformers should always be mounted and transported [illegible] provided so that they may be easily moved.

A bank of transformers in a modern sub-station is shown in Fig. 1,265,* which shows the 10,000 3,000-volt Westinghouse transformers in the [illegible] station of the South Metropolitan Electric Light and Power Company The transformers are in three 500-*k*V.A. sets, each set consisting of two single-phase transformers arranged on the Scott system (*see* page 940), receiving three-phase current at 10,000 volts and transforming it to two-phase current at 3,000 volts. Each transformer stands about 7 feet high, weighs about 3 tons, and, it will be noted, is mounted on a truck so that it can be readily moved.

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* [illegible]

The 10,000-volt switchboard at the sub-station is shown in Fig. 1,266. It is of the Reyrolle ironclad type, and consists of two incoming feeder panels and three transformer panels. The farthest switch is racked out, and in front of it is the carriage on which the whole of the oil switch, with the oil tank, can be removed. The transmission lines from the generating station, six and a half miles distant, are in duplicate, and consist of three-phase, three-core lead-covered cables laid underground. The feeder panels to which these transmission lines are brought are provided with reverse-power relays operated by potential transformers in the oil tanks. The transformers are switched on and off in sets as the load rises and falls.

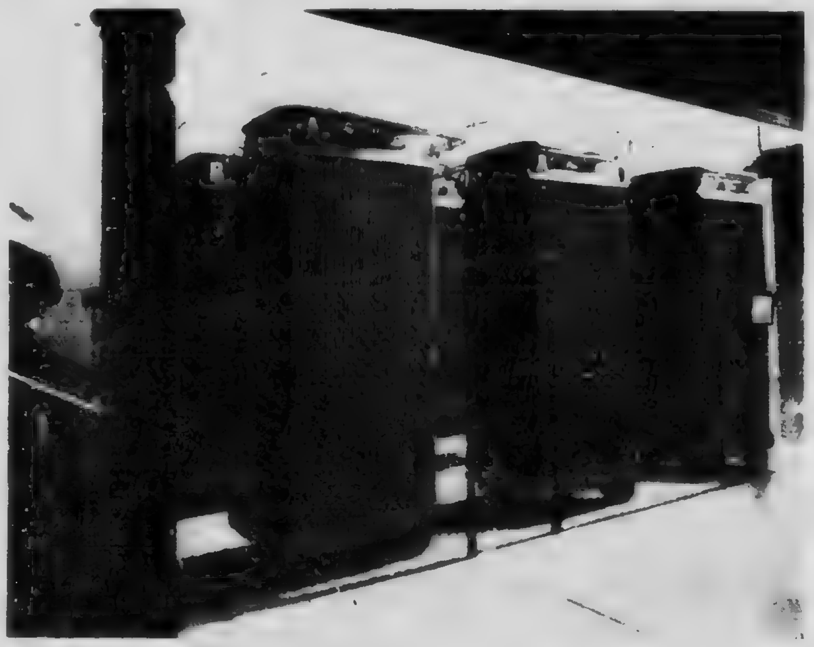


Fig. 1,265.—Bank of Westinghouse Transformers in a London Lighting and Power Sub-station.

A 3,000-volt Ferranti switchboard is shown in Fig. 1,267. It is of the ironclad type, and consists of three two-phase transformer panels in the centre, flanked by seven single-phase feeder panels. The busbars in separate longitudinal cubicles for each phase run along the top of the board, and can be seen in the two compartments from which the covers have been removed. The switches are directly operated by the handles projecting to the front of the board; they are of the oil-break type with the usual over-load release and time-limit attachments.

The necessity for the separate cell structure wherever dangerous voltages are being used has been dealt with in considering the switch gear of generating stations (*see* page 557), and the same reasons hold in connection with sub-station work. Fig. 1,268 shows a section of a Pennsylvania sub-station, in which the busbars, series transformers, fuses, and most of the disconnecting switches are mounted in separate compartments. The roof trusses are even built through the dividing wall of the cell structure, so that economy of space may be attained. Connections to and from the oil switches are made in cambric-insulated wire laid in fibre conduits mounted in the concrete wall. The incoming 10,000-volt three-phase lines are aerial, and the station is protected with the usual horn-gap and aluminium cell lightning arresters described in the next chapter. The live lines go through choking coils and proper inlet tubes direct to the oil switches, whence they continue through disconnecting links and selector switches to one or other of the

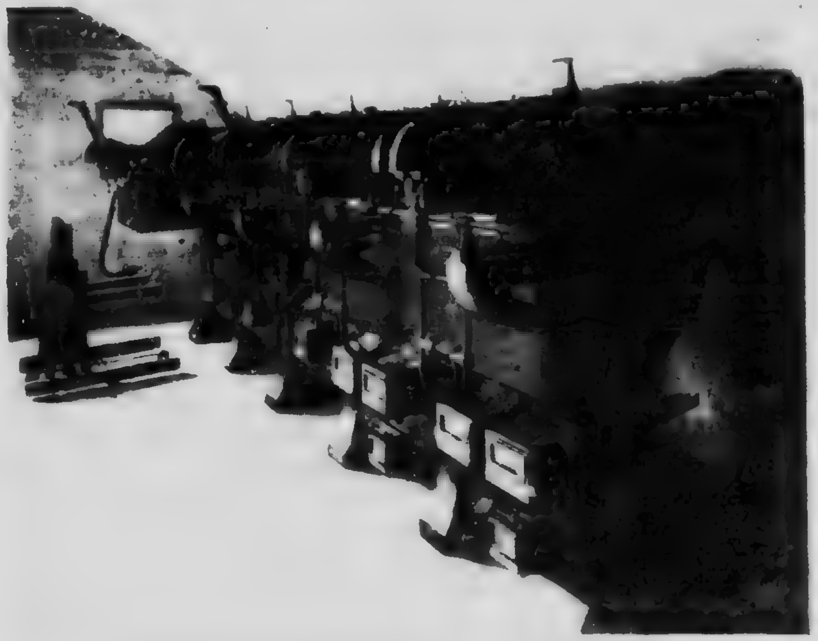
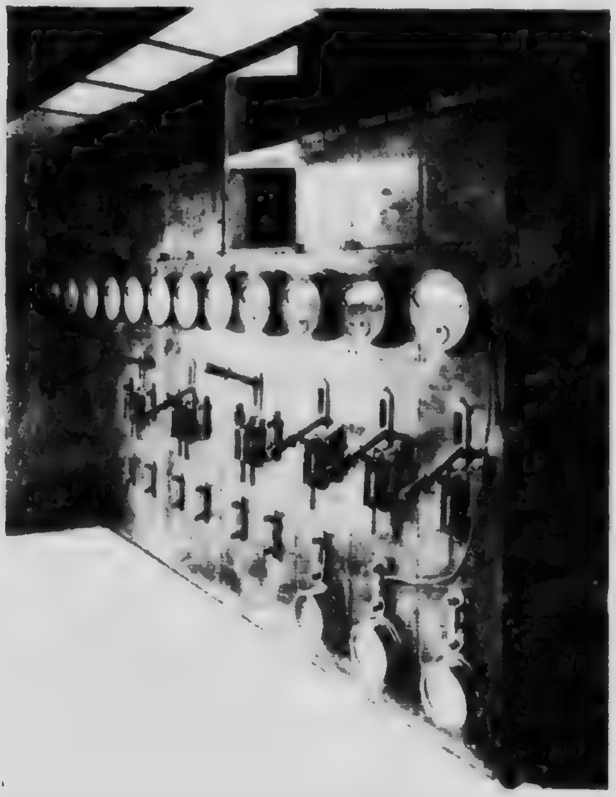


Fig. 1,267.—Reyrolle 11,000-volt Ironclad Switchboard in the Catford Transformer Sub-station double busbars. This double busbar arrangement is necessary where different combinations of high-voltage lines are desirable. From the busbars the current is taken to the primaries of the transformers, and it should be noted that disconnecting switches are installed on both the high-voltage and the low-voltage sides of the transformers, so that a single transformer can be disconnected without interfering with the service. The low-voltage (2,200 volts) busbars are also doubled; the oil switches are mounted overhead, but are directly worked by levers and trackers from the low-voltage switchboard, which is directly in front of the high-voltage board.



F[illegible]—[illegible] it Ironclad Switchboard in Catford Transformer Sub-station.

This section would not be complete without some reference to the outdoor stations which have been erected within the range of the voltages with which we are at present dealing, and quite apart from the chief reasons which have rendered outdoor construction almost imperative with the higher transmission voltages referred to in the last chapter.

A typical station of this kind is shown in Fig. 1,269. It is erected in the open to tap a 10,000 to 20,000 transmission line for the purpose of supplying a small hamlet or a power consumer whose requirements would not justify the erection and maintenance of a building. The three single-phase transformers are erected on a tower construction some feet above the ground; and above them are pole-top switches, fuses, choking coils, etc. No regulators or switches are installed on the low voltage circuits of the transformer; but if regulators are necessary an outdoor pole type has been devised and can be used.

The advantages of such an outdoor installation are the saving of the cost of a building and the lower cost of the high-voltage apparatus. On the other hand, the apparatus must be made weather proof, and the quality of the high-voltage apparatus is not so good nor the construction so safe. The rate of depreciation must also be greater, and the facilities for inspection and repairs less. Finally, there is more liability for accidents caused by intruders and trespassers.

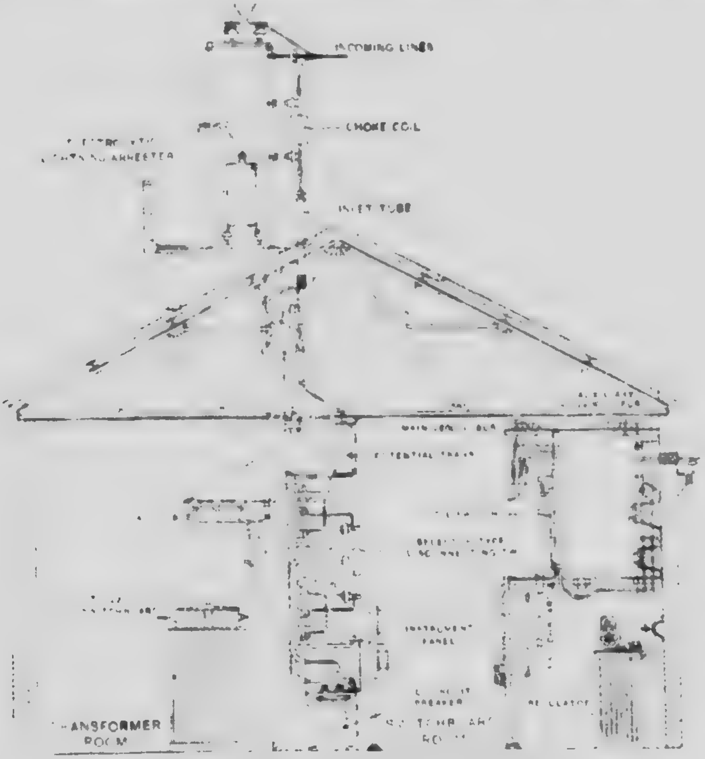
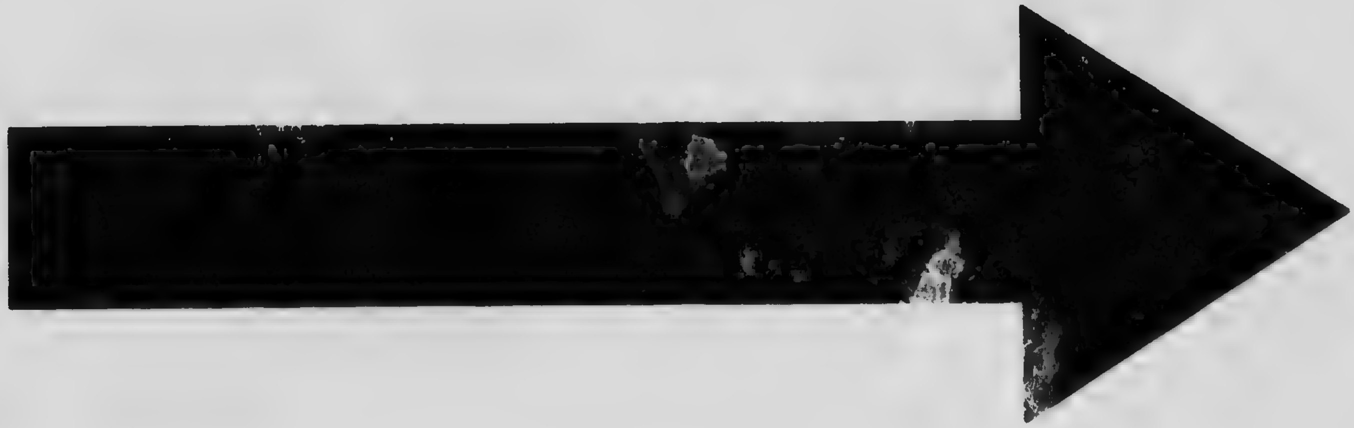


Fig. [illegible].—Section of [illegible] Sub-station

I. (i.).—HIGH-VOLTAGE SUB-STATIONS

When we pass from the moderate voltages which are the highest used in the static transformer stations described in the last section to the high voltages of 30,000 to 150,000 volts or more used in some modern transmission systems (see Chapter XI.), we find that the satisfying of the



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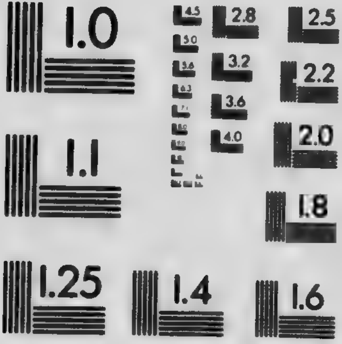

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electrical and other conditions for sub-station working has profoundly modified the whole design of the installation. This is the more to be wondered at when it is noted that we are concerned only with static transformers and the necessary appliances for switching and protection, and that the moving machinery of kinetic transformers has not to be considered, as such machinery only utilises voltages of the magnitude already dealt with.

One difficulty in treating this part of the subject arises from the rapid development of recent years—a development which is still in progress—though a good deal of standardisation of details has already taken place. There are many such high-voltage stations now in existence, and, though it would be impossible to describe all the varieties, the stations selected may be regarded as fairly typical. They divide into two main classes according as they are housed in specially erected buildings, like other types of sub-stations (indoor stations), or are erected in the open without any special protection from the weather (outdoor stations).

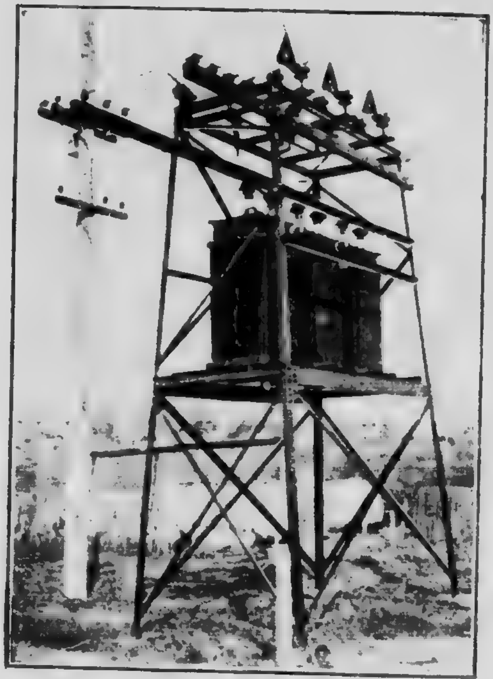


Fig. 1,269.—Moderate Voltage (20,000 volts) Outdoor Sub-station.

Indoor Sub-stations.—A typical New England sub-station for handling power supplied at 33,000 volts is shown in section in Fig. 1,270.[*] It is at Lee, in Massachusetts, and is on the Berkshire Street Railway system, the generating stations of which are at Pittsfield and Xylonite, fifteen and thirty-three miles distant respectively. Two 33,000-volt supply lines enter the sub-station, the lines leaving the station being: (i.) two 33,000-volt lines and one 13,000-volt line for sub-stations farther down the system; and (ii.) the continuous-current line for the local street railway service. The building, which measures 64 feet by 81 feet in plan, is a one-storey building, so designed as to avoid any doubling back of circuits, the advance of the energy through the building being continuous. It is divided into three fireproof sections: The first one, on the right of Fig. 1,270, is 27.5 feet wide, receives the

[*] This and the two following figures are from the *Electric Railway Journal*, of New York.

incoming current, and contains the busbars and high-voltage switches only. Each transmission line A is terminated 10 feet above the roof level with the usual horn and aluminium-cell lightning arresters. A little distance from its termination the line is tapped by the incoming lead *a*, which is led through a special reinforced concrete roof entrance, conical in shape. The top of the cone is provided with a five-part porcelain insulator through which the line passes to insulated terminals, between which is an air-core choking coil to check surges: The appearance of the entering lines, as seen from below, coming through the entrance cones, is shown in Fig. 1,271, which is reproduced from a photograph. From the choking coil each line is taken through a disconnecting switch *d* and a current transformer to the incoming oil switches B, and then direct to the common 33,000-volt busbars, which are suspended from the ceiling of the room, about 12 feet above the oil switches. The supports and bars are shown diagrammatically in Fig. 1,270, but a better idea of this room, which is the most interesting

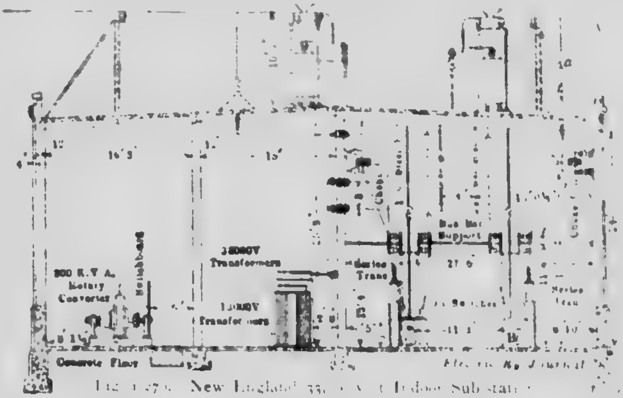


Fig. 1,270.—New England 33,000-volt Indoor Sub-station.

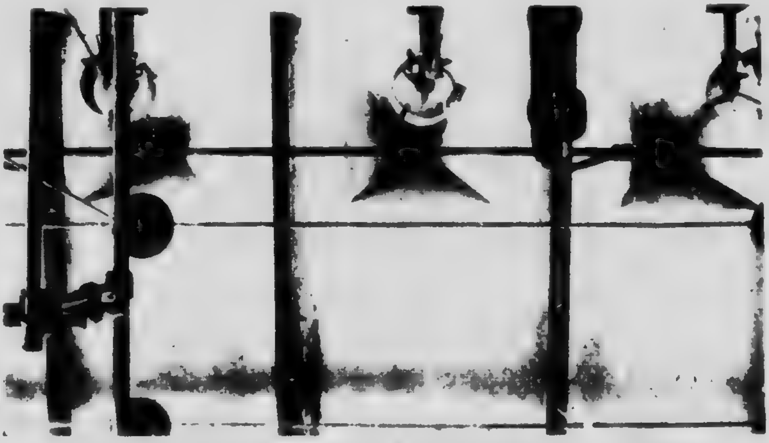


Fig. 1,271.—Three-phase 33,000-volt Leads Entering Sub-station as seen from below.

part of the sub-station, can be obtained from Fig. 1,272, in which the incoming oil switches can be seen on one side of the room and the outgoing ones on the other, whilst overhead are the insulated busbars.

The oil switches are of the general high-voltage type described at page 1248, but are solenoid-operated with remote-control; between them and the busbar disconnectors are interpolated. These can be seen clearly above the switches in Fig. 1,272. They are mounted on pin-type insulators, fixed horizontally to steel channel iron, supported on vertical standards of iron piping. The busbars supply 33,000-volt current through the outgoing oil switches D (Fig. 1,270) to (i.) the two outgoing 33,000-volt lines, which, after passing through choking coils, are led out through the next room to the roof, where the arrangements are similar to those on the incoming side; (ii.) the 33,000-13,000-volt transformers, whose secondary circuits are not shown in Fig. 1,270, but from which the 13,000-volt circuit is led directly out of the station for further transmission; and (iii.) the 33,000–370-volt transformers for the local continuous-current supply through the rotary converters. All these outgoing leads pass through current transformers, as well as the disconnectors, and then through the 12-inch fireproof brick wall, in passing through which they are insulated with the Ohio Brass Company's insulating bushings. In general a spacing of 3 feet is maintained between adjacent high-voltage conductors throughout the station.

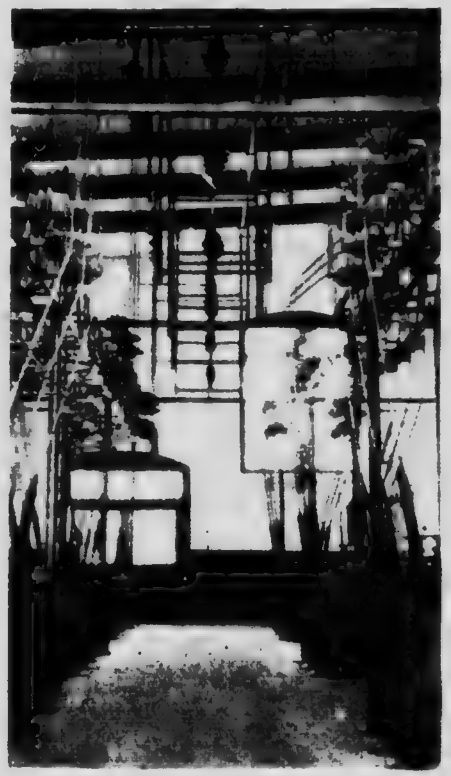


Fig. 1,272.—33,000-volt Oil Switches and Busbars in Sub-station.

For the 13,000-volt line, No. (ii.) above, the transformers are in two banks, each of 110-kilowatts capacity. For the rotary converters the 370-volt cables are run from the transformer secondaries through flow ducts to the starting panels, and thence to the rotaries, the continuous-current side of which offers no point of interest not elsewhere dealt with.

One of the new solutions of old problems which have to be reconsidered because of the increase in the voltage is shown in Fig. 1,273, which illustrates the method adopted by the Eastern Michigan Power Company for bringing the high-voltage supply into the interior of a sub-station. The figure shows the side of the Zilwaukee sub-station with

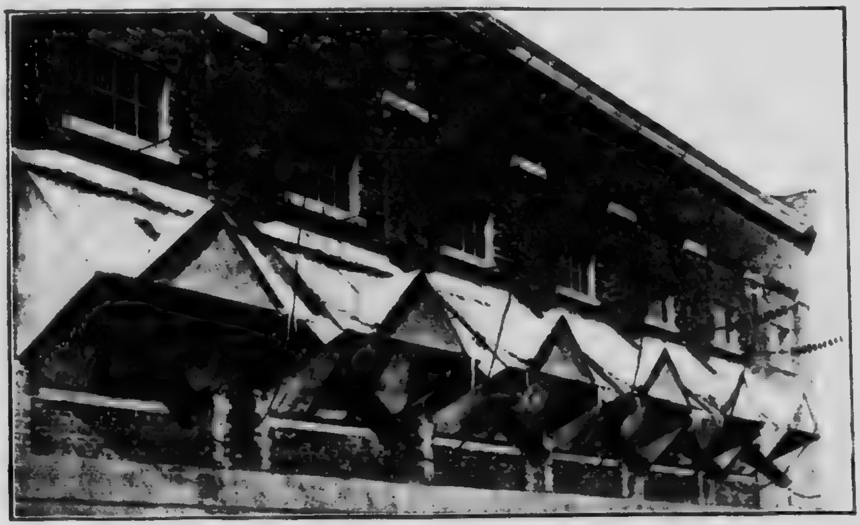


Fig. 1,273 Two Three-phase Lines at 140,000 Volts entering Zilwaukee Sub-station

the entering 140,000-volt leads, of which there are six, the three-phase transmission being duplicated. In the first place the dead ends of the six lines have to be attached to the strings of insulators shown and drawn taut. These strings, over 5 feet long, consist of ten 10-inch insulators described elsewhere (*see* page 1131). From the ends of the line conductor-jumpers of special construction carry on the conducting circuits to the specially designed insulated plugs, which carry the conducting circuit through the wall. One of these entrance insulators is shown

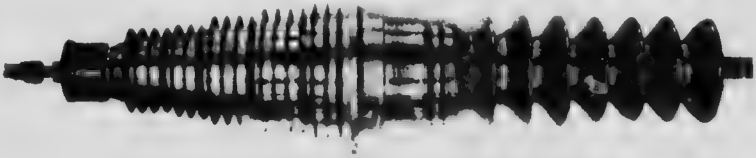


Fig. 1,274.—Entrance Insulator at the Zilwaukee Sub-station

separately in Fig. 1,274; from tip to tip it measures 10 feet 6 inches, of which 6 feet, the end with the coarser corrugations, is outside the building, and is directed downwards. The inlets to the building are entirely closed and weather-proof, and the insulators are carried by an iron-ring casting fixed in framing which is at an angle of 45 degrees, and of which the middle panel, made of sheet metal, is removable, so that insulators may be changed easily if desired. The outer ends of the live wires are protected from roof drippings by a shelter projecting about 3 feet. The pressboard leakage rings, some eighteen in number, on the inner end of the insulator, and the coarser corrugations on the outer end, are designed to increase the length of the leakage path to earth, which may be taken to be at the central clamping ring. Aluminium-cell lightning arresters, not shown in Fig. 1,273, are tapped on to the live wires just outside the entrance jumpers.

The interior of the station is shown in Fig. 1,275, in which, on the left-hand side, will be seen the inner ends of the entrance insulators just described. From these insulators the lines are led through single-pole 140,000-volt oil switches on the left to the busbars, which are made of 1¼-in. iron pipe suspended, as shown, by disc insulators from the ceiling. These oil switches are hand operated from lever panels, and are more fully described elsewhere (*see* page 1248).

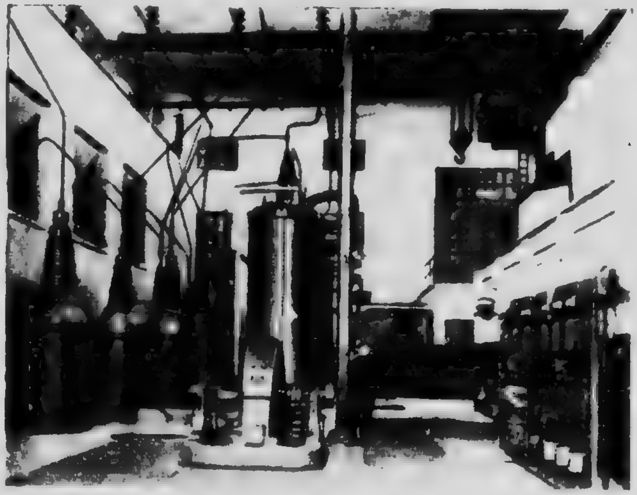
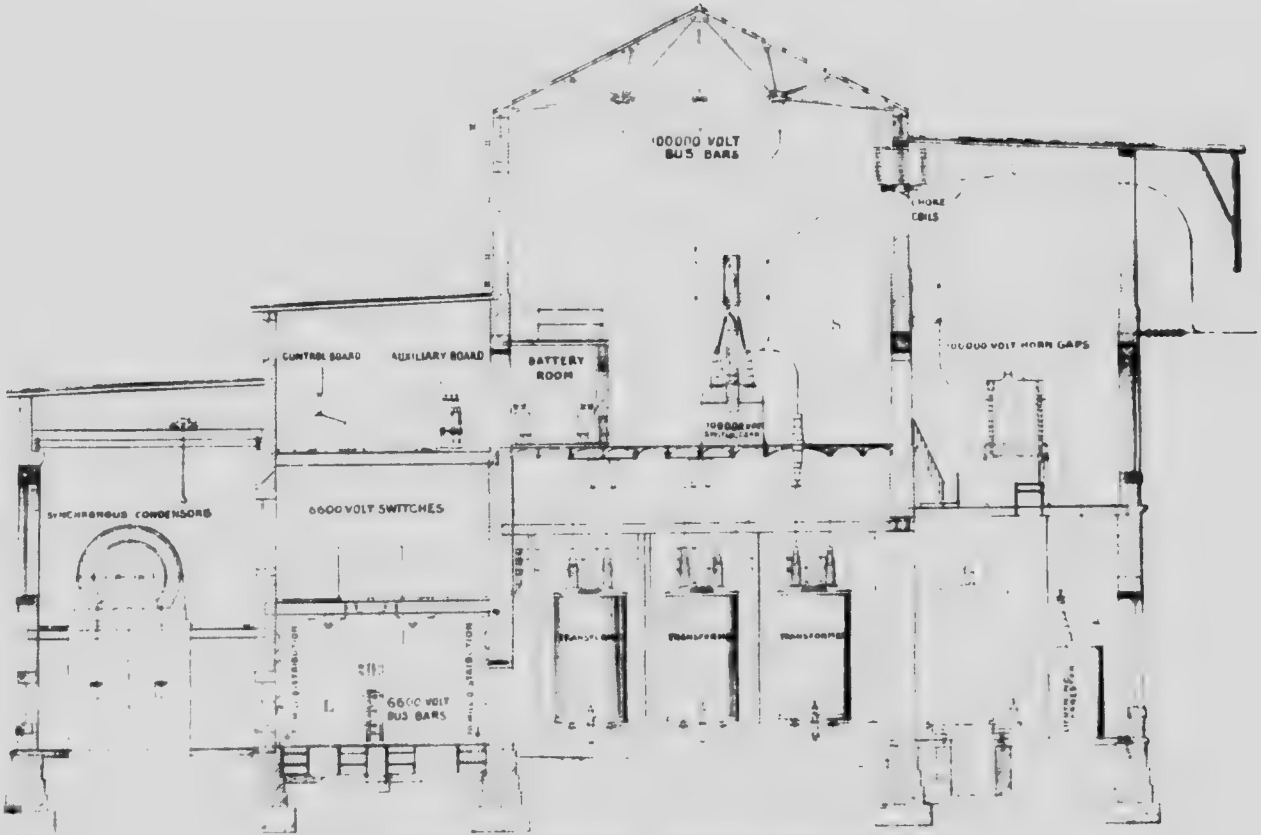


Fig. 1,275.—Zilwaukee Sub-station handling Power at 140,000 Volts.

From the overhead busbars the current is led to the 3,000 kilovolt-ampere static transformers seen in the middle of Fig. 1,275. These huge transformers, which cover a floor space of 11 feet by 5 feet and stand 14 feet 6 inches high to the top of the casing, are described elsewhere (*see* page 926). In this station the 140,000-volt primaries are mesh-connected, and the secondaries consist of (i.) a 22,000-volt coil with an 11,000-volt tapping, and (ii.) two 370-volt coils, each with a full-load output of 125 kilowatts to supply the rotary converter seen in the front of Fig. 1,275. This is a 300-kilowatt 500-volt machine, and its size forms a striking contrast to the size of the transformers immediately behind it. The 22,000- and 11,000-volt lines leave the station on the side opposite to that at which the 140,000-



[illegible] High Voltage [illegible] Receiving Substation at Parel, Bombay volt lines enter, and supply power to other sub-stations farther down the system. The panel switchboard for the rotary converter may be noted on the right-hand side.

As another example of a high-voltage indoor sub-station, Fig. 1,276, taken from a paper read by Mr. Dickenson before the Institution of Electrical Engineers in 1915, gives a cross-sectional elevation of the Bombay receiving sub-station of the Tata Hydro-Electric Power Supply Company, Limited, for the supply of electric power to that city from a power house on the western ghats, forty-three miles away. The transmission voltage is 100,000 volts at fifty periods, and the receiving sub-station is designed to handle ultimately nearly 75,000 kilovolt-amperes in eight three-phase step-down transformer banks of 9,360 kilovolt-amperes each, there being four incoming three-phase lines. An external view of the first part of the sub-station erected is given in Fig. 1,277, which also shows the terminal pole for two of the three-phase incoming lines. The 100,000-volt lines attached to anchor lines of insulators enter the building under a hooded inlet A as shown on the right of Fig. 1,276. Before passing into the high-voltage switch-room S a tap is taken off through a disconnecting switch *d* to the horn-gap arrester, on the earth side of which is interposed an aluminium cell arrester. The line then passes through choking coils into room S, which contains the high-voltage single-pole solenoid-operated oil switches, the disconnecting switches, and the high-voltage busbars. Each three-phase group has current transformers on each phase and inverse time-limit series relays on two phases, with disconnecting switches between the incoming line and the oil switch and between the oil switch and the 100,000-volt busbars. The general appearance of such a room can be inferred from Fig. 1,278, which shows the corresponding room at the generator end of the transmission line, in which also the 100,000-volt busbars are suspended from the roof.

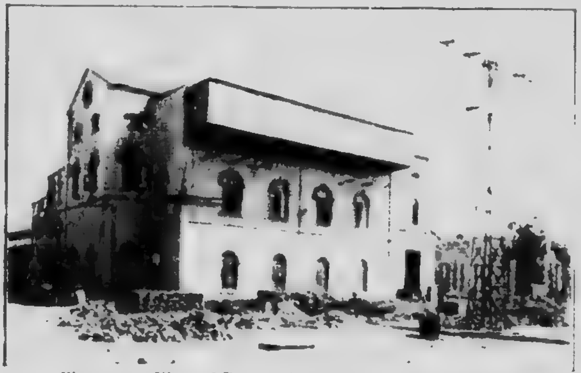


Fig. 1,277.—View of Parel Sub-station under Construction

From the busbar three-phase leads are taken to the primary terminals of the step-down transformers. Each bank of transformers consists of three single-phase General Electric oil-immersed water-cooled static transformers with both primaries and secondaries mesh-connected. Each single-phase transformer is rated at 3,120 kilovolt-amperes, and steps down the voltage from 85,800 to 6,600 volts. The secondaries, as shown on the left-hand side of Fig. 1,276, are connected to the 6,600-volt busbars through triple-pole automatic motor-operated oil switches and single-pole disconnecting switches. The transformers, which are similar to those described elsewhere (*see* page 926), can take a 20 per cent. overload for ten hours without injurious heating, provided 1,450 gallons per hour of cooling water is circulated. The arrangements for the water supply to the transformers are very complete.

From the 6,600-volt busbars, which are shown in the middle of room 1 (Fig. 1,276) the sub-station arrangements follow, with some minor variations of detail, the standard practice described elsewhere.

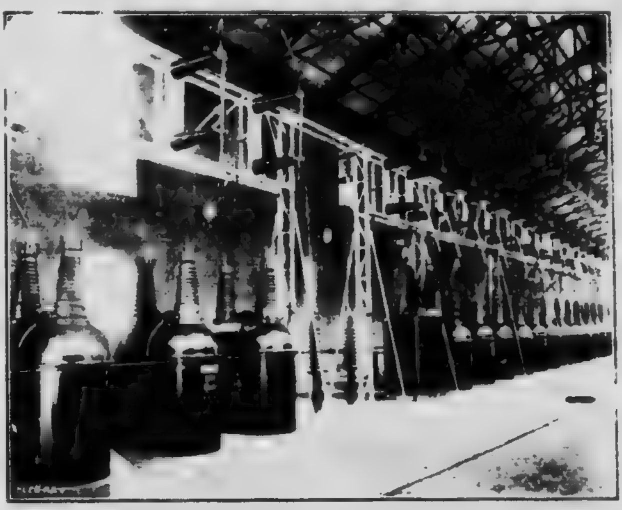


Fig. 1,278.—100,000-volt Switch Gallery with Busbars and Disconnecting Line

Outdoor Sub-stations.—During the last few years there has been rapidly developed, more especially in the United States and Canada, a type of high-voltage sub-station in which practically the whole of the apparatus is in the open air without any protective building. The main reason for this development has undoubtedly been a desire to reduce the capital charges by saving the cost of the large and expensive buildings which would be required to house the transforming, switching, and protective gear which, as will be apparent from the foregoing illustrations, is much more cumbrous for such high voltages than for the more usual voltages reached in this country.

The change has introduced many interesting new problems about which much might be written, but it will be sufficient for our present purpose if we briefly indicate the advantages and disadvantages claimed and admitted by the engineers responsible for designing and working these stations. They have been summed up as follows * :

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* *Electrician*, Vol. LXXIII., p. 1005, and Oct. [illegible]

Advantages	*Disadvantages*
Lower first cost.	Repairs.
Ease of extensions.	Operating risks.
Reduction of fire risk.	Danger to the public.
Simplicity of lay-out.	Appearance.

If our readers will keep these points in mind in reading the following descriptions they will be able, without further exposition, to appreciate the chief factors of the problems presented.

In the design of these outdoor sub-stations, by keeping in view a few general principles, an amount of standardisation has been rapidly attained which has materially and economically affected the capital and maintenance outlays. The general principles involved may be briefly summarised as follows: In the first place the utilisation, in all details of the high-voltage overhead work, of the same insulators, fittings, conductors, etc., as have been used in the transmission line. Secondly, to extend this principle to the steel erections, which in weight, factor of safety and method of erection are similar to the corresponding towers, &c., used in the transmission lines. Thirdly, to design the steel erections and equipment in units, so that different combinations of these units shall provide for different local circumstances, and also for extensions as the load increases. As a detail,

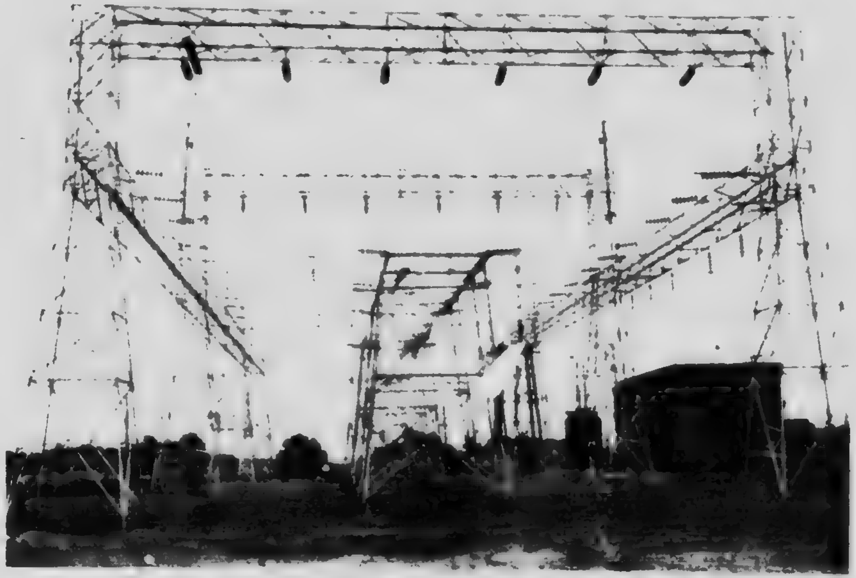


Fig. 1,279.—Supporting Steel-work and Bus-bars of a High-voltage Sub-station in applying these principles definite heights are selected for the high- and low-voltage bus-bars, and the supporting structures are designed for these heights. Thirty feet has been adopted in a fair number of cases as a convenient standard height for the high-voltage bus-bars, and 18 feet as the height for the low-voltage bus-bars.

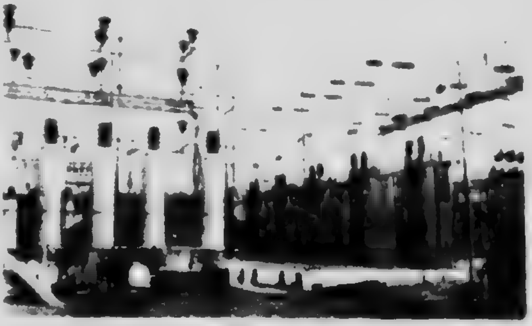


Fig. 1,280.—Transformers and Lightning Arresters in a 110,000-volt Outdoor Sub-station.

How these principles can be applied is illustrated in Fig. 1,279, which is a view of a sub-station of the Alabama Power Company when partly erected. The figure shows the supporting steel work, with the high-voltage busbars, six in number, in position, and supported by the high-level box girder guides; the insulators used are of the ordinary string type used on the transmission line. The view was taken before the installation of the oil switches, lightning arresters, transformers, and other electrical equipment. The building on the right is the low-voltage part of the sub-station for dealing with the further conversion and distribution of the power after the outdoor station has stepped down the voltage from 110,000 to 22,000 volts.

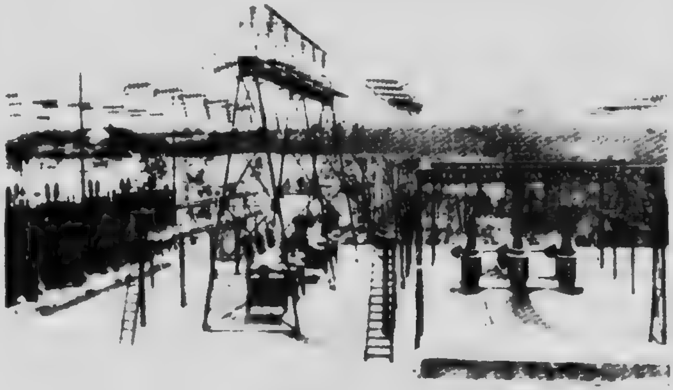


Fig. 1,281.—A 110,000-volt Outdoor Sub-station after a Blizzard.

The reasons why such high erections are necessary and the appearance of some of the electrical plant when erected, are shown in Fig. 1,280, which is a view of a bank of transformers on the right-hand side and a grouped lightning arresters on the left. The concrete supports for the transformers and their high- and low-voltage terminals are clearly seen, and above are the horn-gap lightning arresters. The view is of a part of the Millbury sub-station of the Connecticut River

Transmission Company, about six miles from Worcester, Mass. The transmission voltage is 110,000. A view of another part of the same station, as it appeared after a blizzard, is given in Fig. 1,281. In this view the single-pole oil switches, three in each group, appear in the middle and on the right of the picture, and the transformers on the left. It is of interest to note that all the snow has been melted off the transformers by the waste heat which they produce, whilst the switches, in which no such heat should be produced, are thickly covered with snow. The appearance of these switches under such severe circumstances is still better seen in Fig. 1,282. In this view there can also be seen the choking coils, which are interposed between the line and the switch terminals.

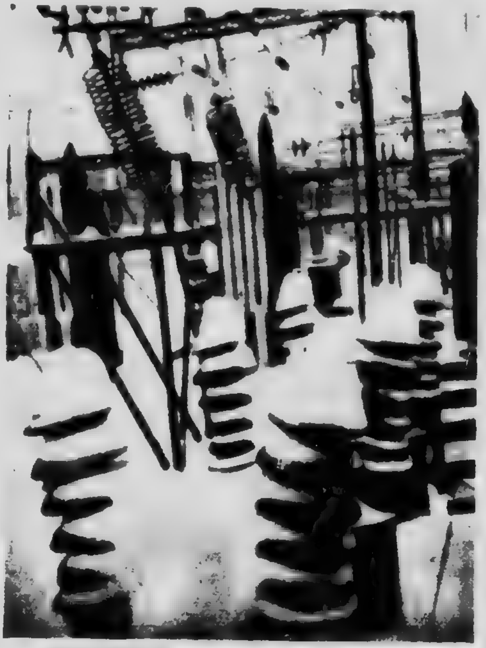


Fig. 1,282.—Outdoor Oil Switches after a Blizzard.

The complete lay-out of a large outdoor high-voltage sub-station is shown in Fig. 1,283, which is a plan of the Atlanta sub-station of the Georgia Railway and Power Company, whose generating station is at Tallulah Falls, Georgia, ninety miles from Atlanta. The transmission pressure is 110,000 volts. A perspective view of the sub-station, as seen from a point on the left of Fig. 1,283, behind the low-voltage building, is given in Fig. 1,284. By comparing the two figures most of the main details can be made out.

The sub-station is rated to handle 60,000 kilowatts, its first equipment, in 1914, being with apparatus for half its capacity. The incoming lines are all at 110,000 volts, as are also three outgoing lines, the term "line" being used to specify the *three* conductors of the three-phase transmission. It is necessary to remember this because for each "line" the apparatus of all kinds is in triplicate, no three-phase transformers or switches being used.

On the left-hand side of the plan (Fig. 1,283), along the line B B′, are the structures supporting the horn gaps and choking coils at the ends of the overhead high-voltage lines. There are similar structures at A and A′ on either side of the main building, and the details of the apparatus at A and the two groups along the line B B′ can be made out in Fig. 1,284.

The first two groups on the line B B′ had not been installed when the photograph was taken.

On either side of the centre behind the main building are the double

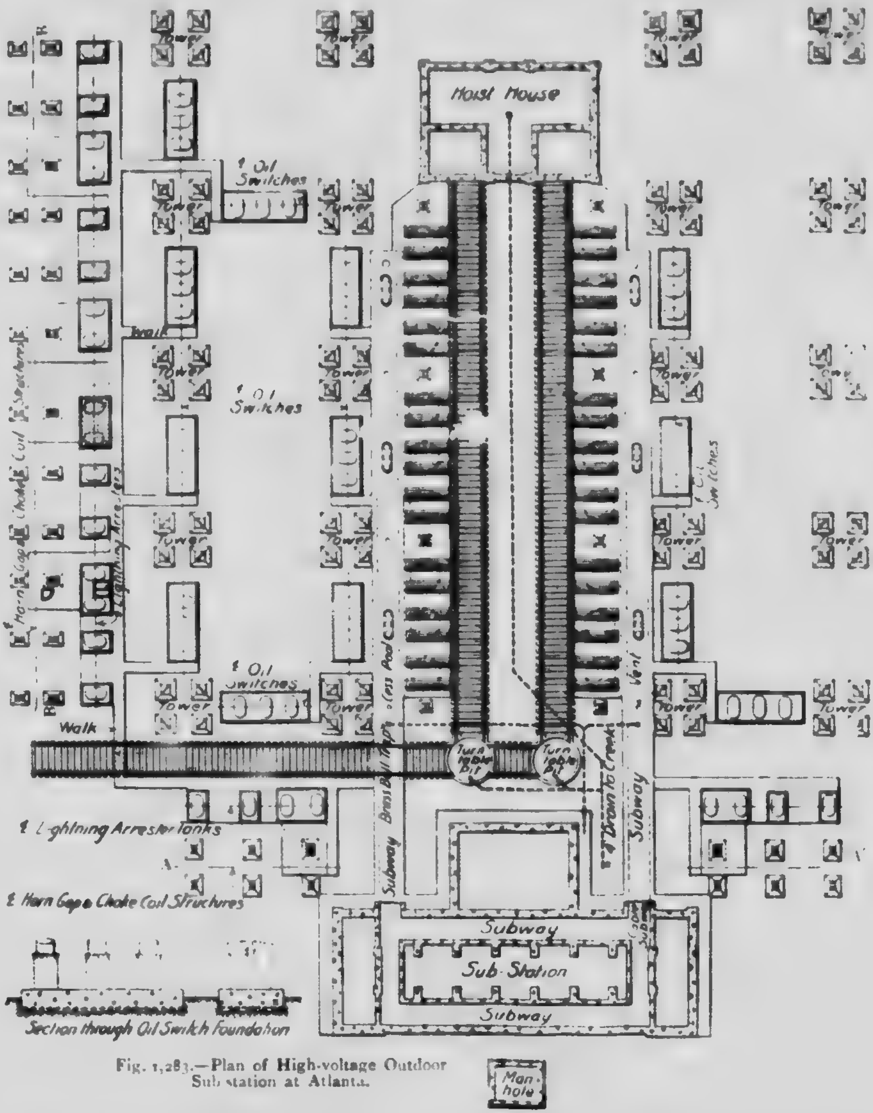


Fig. 1,283.—Plan of High-voltage Outdoor Sub-station at Atlanta.

rows of tall quadrangular lattice towers, which support the high-cross girders from which the busbars, etc., are suspended. Between the foundations of the towers are placed the oil switches, each a single-pole switch, which are interposed electrically between the transmission lines and the busbars on the one hand and between the busbars and the high-voltage terminals of the transformers on the other. Some of these oil switches can be very clearly seen in Fig. 1,284. The busbars are of copper tubing supported by hangers from a ½-inch copper-clad catenary, which is supported from the steel framework by strings of disc insulators. Disconnecting switches are inserted at the usual points, and the contacts are so protected by hoods that they can be operated from the ground in severe wintry weather.

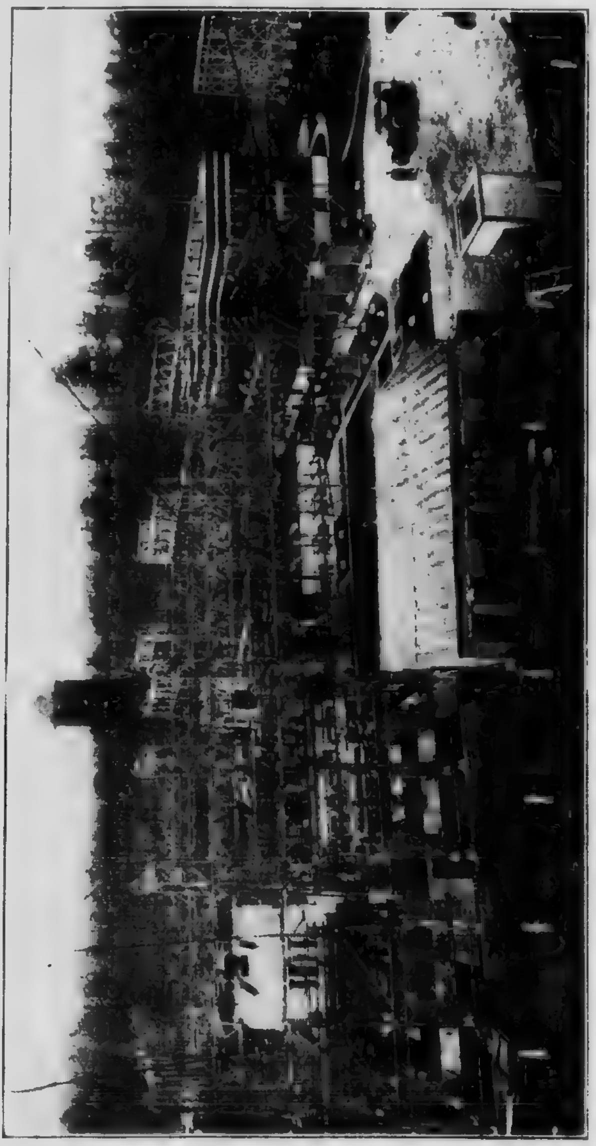


Fig. 1,284.—View of the Atlanta High-voltage (110,000 volts) Sub-station.

The positions of the eighteen transformers (six groups), which will take the full load of the station, is shown in the central part of the plan (Fig. 1,283), and the three groups installed in 1914 are shown in Fig. 1,285, which is from a point of view in the central gangway facing the white house seen in Fig. 1,284, and which in Fig. 1,285 is marked as the "repair shop." Each single-phase transformer has a capacity of 3,333 kilovolt-amperes, and steps down the voltage from 110,000 to 11,000 volts. The transformers are water-cooled, and are supplied with cooling water from the water-storage tank, which can be seen in the background in Fig. 1,284. Besides the water distribution system there are oil mains connecting the different transformers with the filter press and the oil-storage tank in such a way that the oil may be forced in either direction through the system. Along the whole length of the transformer space, and at right angles with turntables at the corners, there are trolley lines, as shown in Fig. 1,285. By means of these and the small trolley shown at A in Fig. 1,285, any transformer, oil switch or other heavy piece of apparatus can be rapidly transferred to the repair shop for overhauling and repair. This repair shop is, of course, well equipped for the work it is called upon to do.

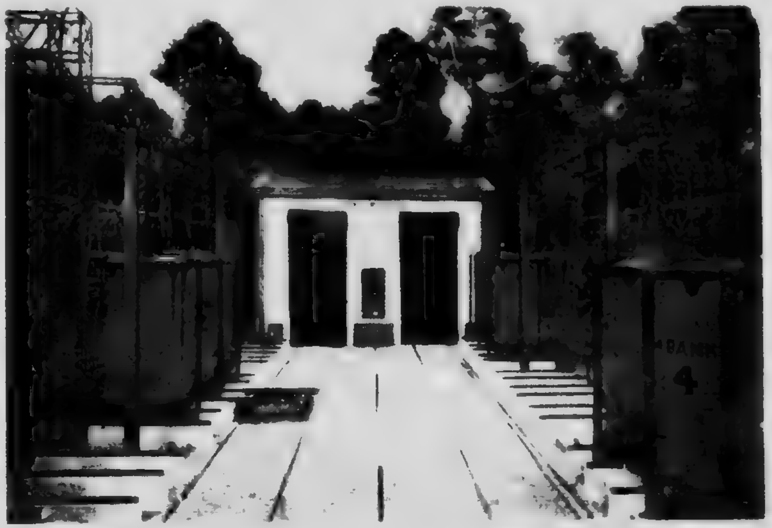


Fig. 1,285.—Six 3,300 kv.a. 110,000 to 11,000-volt. Transformers in Atlanta Substation.

The low-voltage (11,000 volts) leads are carried from the top of the back of the transformer to mesh busbars supported on a pipe framework. From the busbars the leads are carried through roof-entrance bushings set in iron castings into the "subway," which is shown in Fig. 1,283, running behind the transformer banks. The subway, which is 7 feet high, is shown separately in Fig. 1,286. The 11,000-volt leads entering through the roof are connected to $\frac{13}{16}$-in. tubing, which is run at the side of the subway along concrete shelves, on which the tubing is supported on porcelain insulators. The subway runs right into the low-voltage main building, and carries the leads on to their respective oil switches therein.

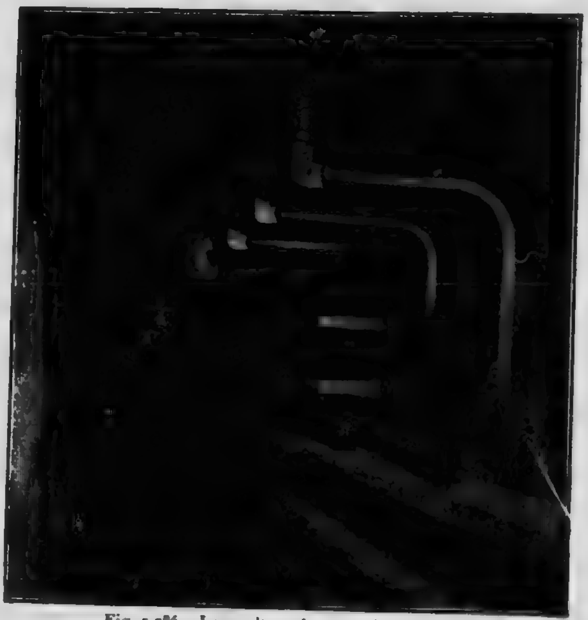


Fig. 1,286.—Low-voltage (11,000 volts) Subway.

The phases of each "line" are separated throughout by masonry barriers.

In this building is situated the remote-control switchboard (Fig. 1,287), from which the entire station is controlled. It is of the desk pattern (*see also* Figs. 547 and 552 to 554), with the measuring instruments on vertical panels at the back, and with mimic busbars and connectors on the top of the desk. The high-voltage sections are indicated by brass strips and the low-voltage ones by copper strips. The control is exercised through pull-button switches, which operate in circuits energised by a 250-volt 40-ampere-hour storage battery, which is charged by two 10-kilowatt motor-generator sets. These motor generators, as well as the pumps, continuous-current lighting main, etc., are energised from two banks, each of three kilovolt-ampere transformers, 11,000-

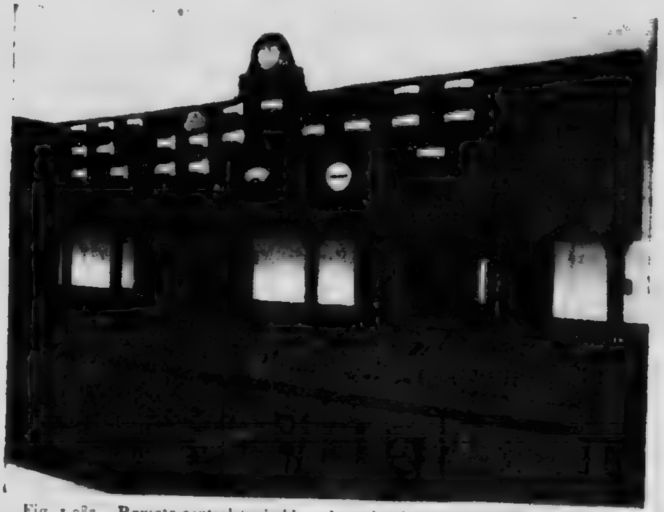
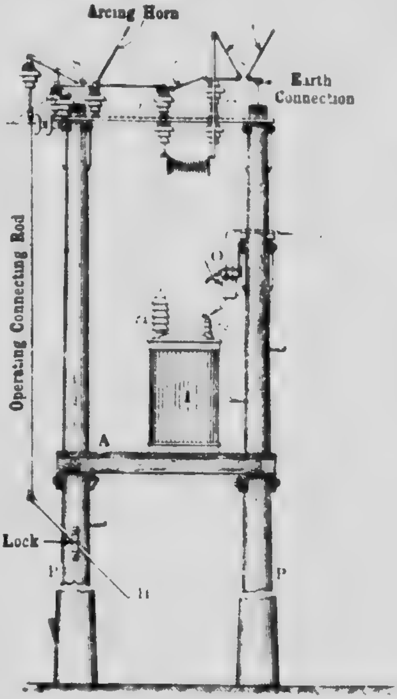


Fig. 1,287. Remote-control Switchboard at the Atlanta High-voltage Outdoor Sub-station.

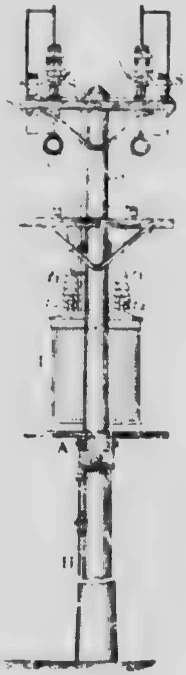
110–220 volts, and three 25-kilovolt-ampere 11,000–440-volt transformers.

The outgoing low-voltage conductors, fifteen in all, are each of 200-amperes capacity. Nine of these are underground, and six (two three-phase sets) are overhead. The structure for carrying the dead ends of the 11,000-volt overhead lines can be seen in front of the building in Fig. 1,284.



SIDE VIEW.

Fig. 1,283.

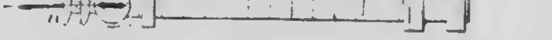


END VIEW.

Fig. 1,284.

Elevations of a Single-phase 50-kw. 33,000-volt Outdoor Sub-station.

Reasons quite different from those which have led to the development of the large outdoor sub-stations just described have brought about the installation of another type of outdoor station. In the Middle and Far West states and provinces on the North American continent, where labour is often very scarce, a demand has sprung up among the farmers for electric power, which, it seems reasonable to suppose, could be tapped from the high-voltage transmission lines passing over or within sight of their farms. Central station managers have not been slow to recognise the commercial value of the demand and to give attention to the problems presented.



PLAN VIEW.

Fig. 1,285. Plan of Single-phase 33,000-volt Outdoor Sub-station

A "step-down" sub-station in the vicinity of the long-distance transmission line is evidently required but the demand is small and very scattered, so that in many cases a maximum output of 50 kilowatts would probably supply all the power that is likely to be required within a reasonable distributing distance of the tapping point. Notwithstanding, it is essential that the capital and maintenance costs per kilowatt must be kept down if the charges are to be low enough to attract the necessary customers in order to secure a fair return on the investment.

An important factor in reducing the capital cost is to dispense, if possible, with an enclosing building for the plant. This requires that the installation shall be weatherproof, and in its design the experience gained in the larger stations becomes useful. The details of a single-phase 50-kilowatt station of this kind are given in Figs. 1.288 to 1.290. The whole apparatus is supported on two poles P P, which carry the platform A A by means of the iron framework shown. A side elevation of the arrangement is given in Fig. 1.288 and an end elevation in Fig. 1.289, whilst Fig. 1.290 supplies a plan on a larger scale. The principal apparatus is the static transformer T, of which $t_1 t_1$ are the primary terminals and $t_2 t_2$, the secondary terminals. The particular apparatus shown was used to step-down 33,000 volts on the incoming line L L to 220 volts on the outgoing line $l\,l$. In this case switches are provided on both the high- and the low-voltage lines. The high-voltage switch S S is of the double-pole type, and it is operated by the handle H at the bottom of one of the pillars. The transmission lines L L are made fast to the cup insulators $i_1 i_1$ and the triple-shed insulators $i_2 i_2$, and a jumper is carried to the terminal. A fuse f and a choking coil c are inserted in parallel on each line between the insulators i_8 and i_7, the latter sup-

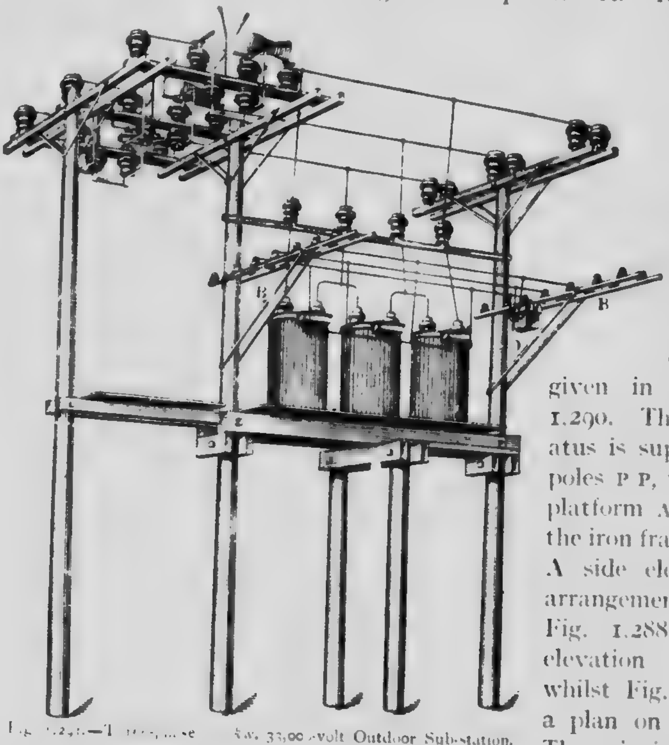


Fig. 1.287.—Three-phase [illegible] kw. 33,000-volt Outdoor Sub-station.

part the insulated side of the horn-gap g, the other side of which is earthed. From i_6 the high-voltage line goes to the transformer terminals $t_1 t_1$. The secondary terminals $t_2 t_2$ are carried to the iron automatic weather-proof oil switch o, which is supported by the framework a a at a lower level than the high-voltage incoming terminals.

Another station of this kind, 150 kilowatts three-phase, is shown in perspective in Fig. 1.291. The supply is at 33,000 volts and 60 periods, and the apparatus is carried on five poles. All the load switching is done on the low-voltage side. There are three single-phase transformers, with their primaries connected in mesh to the high-voltage lines. The high-voltage equipment, consisting of the insulators, a triple disconnecting switch, fuses, horn-gaps, and choking coils, is carried on a channel-iron framework supported by cross arms. The secondary terminals are carried first to three span wires carried on insulators supported by the brackets B B, one of which carries the non-automatic weather-proof oil switch o, interposed between the transformers and the outgoing load lines. The 33,000 volts is stepped down to 110, 220, and 440 volts, and the low-voltage switch must always be opened in advance of the high-voltage disconnecting switches.

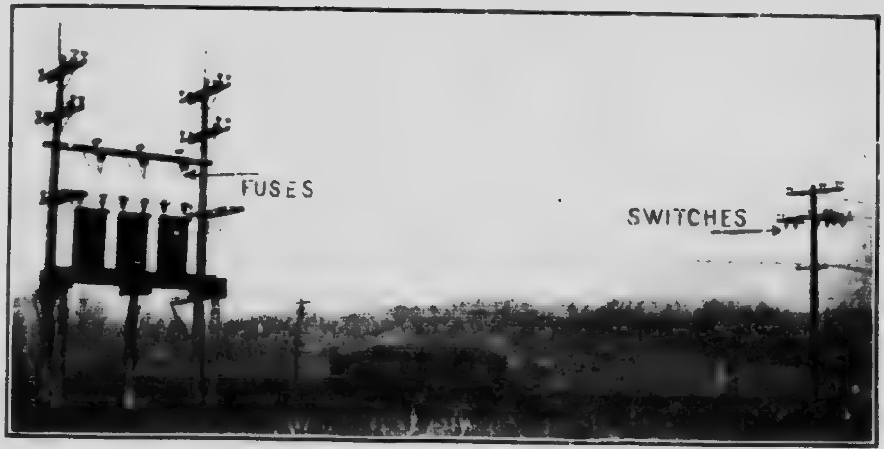


Fig. 1.292. Outdoor 33,000-volt Sub-station for Pump Motors

A somewhat different pattern of three-phase 33,000-volt sub-station is shown in Fig. 1.292. This was erected to supply current for operating electrically driven pumps. The high-voltage switches are erected on a neighbouring pole, and the transformers are protected by fuses only. In such cases the main lines must be protected by lightning arresters within a reasonable distance of the station.

Still larger outdoor sub-stations are erected, sufficient to supply a small town. In such cases a little covered-in cupboard is provided on the platform to shelter the panel distribution board, the meters, the distributing oil switches, the relays, and the automatic voltage regulators for the feeders.

The conditions which such exposed stations have to face are very rigorous, for in the winter the whole station may be loaded up with ice, and it may also be subjected to violent thunderstorms and cyclones.

I. (ii.)—OPERATION OF STATIC TRANSFORMER SUB-STATIONS

Most of the apparatus, instruments, switches, fuses, etc., necessary for the equipment of a static transformer sub-station will be found described in other parts of this book, and with one exception it is unnecessary to supplement these descriptions here. Some illustrations have also been given earlier in this chapter, and in the section on generating-station switching, of the switchboards used in static transformer sub-stations. This subject will not therefore be dealt with further in this section. Since there are no moving parts the operation of static transformers only would at first sight appear to be a very simple matter, but, notwithstanding, there are one or two matters in transformer working to which some attention may well be given here, though it will be convenient to postpone till after the next section all those operations which in any modern scheme have to be considered in connection with the combination of static transformers with the kinetic transformers described in Chapter VIII.

In the small transformer sub-stations installed under the footwalks (*see* Fig. 1,258), the transformers, if more than one, are joined up permanently in circuit, and their primaries are on the high-voltage mains, whatever the load on their secondaries may be. This is, of course, an argument against the lavish use of such chambers, which can only be economical where the consumers are few and scattered and individually do not absorb much power. In all cases where the load in the surrounding district is sufficiently concentrated, the sub-station should be provided with switching apparatus for increasing and reducing the number of transformers in circuit as the load fluctuates up and down. For this purpose paralleling appliances will be provided on both the high- and the low-voltage sides, and in connection with the operation of these some interesting points arise.

Paralleling Transformers.—At first sight it might appear that there is very little involved in throwing transformers in and out of circuit which calls for comment, and this is certainly the case in single-phase working and where the transformers are identical in size and construction. In three-phase working, however, and when different types and sizes of transformers have to be paralleled, the case is not so simple.

Single-phase Working. If two transformers have their primaries paralleled on to the same mains, then it is obvious that if the secondaries are to run in parallel it is necessary (i.) that the terminals on the secondary side which are joined together should have the same *polarity*, (ii.) that the transformers should have the same *voltage ratio*, and (iii.) the same percentage *impedance*.

The test for *polarity* is simple, and need only be made when new transformers are being installed and are being permanently connected to the switches, fuses, busbars, etc. The primary terminals of the incoming transformer having been connected in the most convenient manner to the primary circuits, one of the secondary terminals should be connected to one of the secondary busbars, these busbars being alive from the secondaries of the other transformers already in circuit. A suitable voltmeter should then measure the pressure between the other busbar and the unconnected terminal of the incoming transformer. If this pressure be found to be *zero* the polarity is all right and the second terminal can be connected up. If, however, the voltmeter shows *double* the busbar P.D., the first connection made is wrong, and that connection must be crossed over to the other busbar and the other connection made to the first busbar. This test is known technically as "phasing-out."

It is also obvious that the *voltage ratio* should be the same, because if there be a serious difference, say 10 per cent., the two secondary coils, when paralleled and energised from the same primary mains, will behave as two batteries with different voltages joined in parallel. With no working load the difference of the two voltages will cause a heavy current to circulate through the impedances of the two coils which will be in series with one another. As these internal impedances are small compared with the load impedances, it may well happen that this circulating current is heavier even than the load current of the smaller of the two transformers if they be of different capacities. It is easy to make the calculation when the effective impedances at full load are known.

That the third condition should be, at least approximately, fulfilled is also obvious, though its rigorous fulfilment is not essential. It should be explained that for many practical purposes it is convenient to specify the impedance of a transformer by the percentage drop of volts at the secondary terminals on full load, the comparison being made with the voltage ratio. In addition to the voltage ratios being the same for paralleling purposes, the *percentage impedances* as so defined should also be the same, not only in magnitude but in their effect on the phase angle. It is, of course, desirable that the load should be divided, according to their capacities, between all the transformers on the busbars. This will approximately happen at full load if the magnitudes of the percentage impedances be the same, the voltage ratios also being the same, but there may be differences at other loads, unless the characteristics of the transformers are similar. It will not happen, even at full load, if the influence of the impedances on the phase angles be different, that is, if the values of *tan* ϕ, the ratios of inductive reactance to resistance, differ. In this case, the load current will divide in inverse proportion to these impedances, and some of the transformers may thus be overloaded. Further, the coils with the higher values of *tan* ϕ will carry *lagging* currents, and those with the lower values *leading* currents with respect to the phase of the load or line current. This is obviously undesirable, though the matter is not so serious as differences in polarity or voltage ratio.

Voltage ratio, percentage and the characteristic impedance are factors which are involved in the design of the transformer. If the voltage ratio be wrong the transformer must not be paralleled. If, however, the voltages are right but the impedance at full load be too low, matters may be adjusted by the judicious use of a suitable choking coil introduced between the secondary terminals and the busbars.

Ordinary Three-phase Working.—When we turn to the case of polyphase working additional factors are introduced into the problem of paralleling, the most important of these being (i.) that the method of connecting the phases in the different transformers should be such as to make paralleling possible, and (ii.) that, this being assured, the *phase rotation* in the secondary coils of the incoming transformer should be the same as on the secondary busbars of the sub-station.

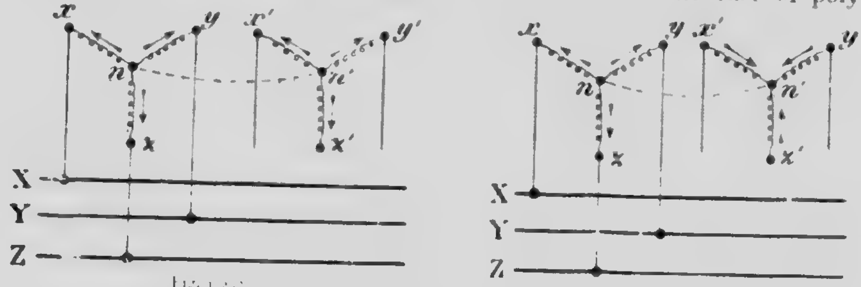


Fig. 1243. Fig. 1244

Paralleling Star-connected Transformers

As regards (i.), the question of paralleling three-phase transformers has already been referred to on page 947, where it has been shown that it is possible by proper attention to voltage ratios to parallel similar connected transformers such as "mesh-mesh" with "mesh-mesh," or "mesh-star" with "mesh-star," and so on. With the same proviso it is also possible to parallel "mesh-mesh" with "star-star," and "mesh-star" with "star-mesh." It has, however, been shown that on account of phase differences it is not possible to parallel "mesh-mesh" or "star-star" banks of transformers on the one hand with "mesh-star" or "star-mesh" banks of transformers on the other.

The question of (ii.) phase rotation was alluded to but not fully dealt with at page 947, and a few lines are therefore necessary here to show how this can be determined in connecting up the transformers in a sub-station.

The simplest case to deal with first is that in which both secondaries are "star" connected, and in which the proper P.D. between any line and the neutral point of the star is 0·577 of the line voltage (see Fig. 962. In Figs. 1,203 and 1,204 let x, y, z represent the three legs of the secondary of a transformer already connected to the busbars X, Y, Z, and x', y', z' the legs of the secondary of the incoming transformer whose primary terminals have already been connected to the primary mains. If now the two neutral points n n' of the stars be connected, the potentials of all the terminals relatively to this neutral connection will be fixed. The factors to be determined are the polarities of the incoming transformer and its phase rotation, and for this purpose voltmeter measurements should be made between each busbar and the terminals x', y', and z'. If the polarities are correct, then, V being the line voltage, the two typical cases will be as follows:--

Case A

Xx' = zero
Yy' = zero
Zz' = zero

Case B

Xx' = zero
Yy' = V
Zz' = V

In Case A both the polarities and the phase rotation are correct and the main switches can be closed. In Case B the polarities are correct but the phase rotation is wrong, but may be adjusted by interchanging the y' and z' labels and then connecting to the busbars, according to the re-markings. There are two obviously possible variations of Case B which call for no comment.

If the polarities be wrong there will be no zero readings of the voltmeter, but some of the readings will be 1·154 V, indicating that the coils of the two secondaries are in series (180° out of phase), through the neutral connection across the terminals of the voltmeter, and the others will be 0·577 V, indicating that the coils across the voltmeter are 60° out of phase. The quickest method of "phasing-out" is to find the combinations giving the higher readings, of which there will be three, and three only. The following are typical cases:

Case C

Xz' 1·154 V
Yx' 1·154 V
Zy' 1·154 V

Case D

Xx' 1·154 V
Yz' 1·154 V
Zy' 1·154 V

On analysis it will be found that the phase rotation is correct in Case C, being counter-clockwise for both sets of vectors taken in cyclical order, and is reversed in Case D, being counter-clockwise for X Y Z and clockwise for x', y', z'. A simple method of making the analysis is to draw a vector diagram in the shape of a six-pointed star, as in Figs. 1,205 and 1,206, and mark three of the vectors 120° apart with arrow-heads directed *outwards* and label them X, Y, and Z. Mark the other three vectors with arrow-heads directed *inwards*, and then label them x', y', and z', so as to bring the above pairs in line; i.e. in Case C, z' being opposite X, x' opposite Y, and y' opposite Z. The result for Case C is shown in Fig. 1,205, and for Case D in Fig. 1,206. To alter the polarities, it will be necessary to reverse the connections of the secondary windings with respect to the neutral point. This will be equivalent in the vector diagrams to sliding the x', y', z' vectors over the opposite X, Y, Z vectors, thus in Fig. 1,205 putting z' on X, x' on Y, and y' on Z. This will be found to have left the phase-rotation unchanged, but it will be desirable to re-label the terminals in accordance with the positions of the coils on the X, Y, Z vectors, z' being changed to x', and so on.

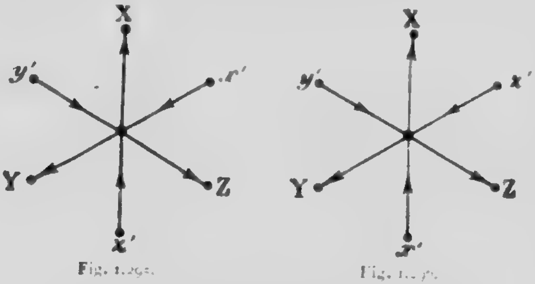


Fig. 1,205. Fig. 1,206.
Vector Diagrams of Transformers with Connections reversed.

In Fig. 1,206 the change of the connections will also have left the phase-rotation unchanged—that is, reversed; but this can also be set right by re-labelling the coils x', y', z' as above, in accordance with their new positions on the X, Y, Z vectors.

If none of the transformers already on the busbars has a star-connected secondary, in order to apply the above method it will be necessary to get the busbar neutral point with suitable star-connected resistances. The following method is, however, more general, and is applicable either to "star" or "mesh" connected secondaries. The student who has carefully read the previous cases should be able to understand these and make, where necessary, the corresponding diagrams.

In the general case, a neutral point not being available, the potentials of the incoming transformer are anchored, as it were, by connecting one, say x', to one of the busbars, say X, thus bringing x' to the same potential as X. If now, on applying the voltmeter test, Y y' and Z z' are found to be zero, the polarities and phase relations are correct, and the transformer can be fully switched on to the busbars. Also, if Y y' and Z z' are found to be the line voltage (V') and Y z' and Z y' zero, the polarities are right, but the phase-rotation is reversed, and the markings of y' and z' must be interchanged.

It may, however, happen that the voltmeter reading of Y y' and Z z'

shows $2\,V'$ in each case whilst $Y z'$ and $Z y'$ are each $= 1{\cdot}73\,V'$. This means that the polarities are wrong and the voltages are in series in the first case, and have a phase difference of 120° in the second; the phase-rotation is, however, correct. In this case paralleling is impossible without reversing the internal connections either of the primaries or the secondaries but not of both. The phase-rotation remains correct.

If, however, $Y y'$ and $Z z'$ each $= 1{\cdot}73\,V'$, whilst $Y z'$ and $Z y'$ each $= 2\,V'$, both the polarity and the phase-rotation are wrong, which will necessitate a reversal of the internal connections, and also a re-labelling of the terminals y' and z'.

Other indications of reversed polarity are furnished by such readings as:—

(i.) $Y y' = V'$, $Z z' = V'$, $Z y' = O$, and $Y z' = 1{\cdot}73\,V$.
(ii.) $Y y' = 1{\cdot}73\,V'$, $Z z' = O$, $Z y' = V$, and $Y z' = V$.

In case (i.) the phase rotation is correct, but in case (ii.) it is reversed.

The above instances do not exhaust all the possible cases, but if mastered no difficulty will be experienced with the cases omitted, especially if, in any new case, the proper diagram be carefully drawn.

Open Mesh or "Vee" Working.—When one side of a "mesh" connected three-phase set is removed, the other two sides, remaining connected to three-phase mains, will continue to handle the load, the full-load capacity being reduced by one-third. The method is known as "open mesh" or "Vee" working. It does not often occur in practice, but when so occurring can be treated for paralleling in the same way as "mesh" connected banks of transformers.

Three-phase to Two-phase Working.—In paralleling banks of transformers connected on the Scott system explained at page 948, and known technically as the "Tee" method of connection, the chief point to be watched in "phasing-out" is that the three-phase windings must be symmetrically connected. If this condition be not fulfilled the two-phase windings will be 30° out of phase.

General Considerations.—Where heavy currents are being handled it is desirable that the leads between the transformers and the busbars or main junction should be of the same length, or that the resistance and reactance of the leads should vary as the capacities of the banks of transformers which they serve.

Transformers should also be paralleled, whenever possible, at the same temperature, or at any rate the differences of temperature and their effect on resistance should not be large.

The paralleling of transformers is independent of the power factor of the load; if the paralleling is satisfactory at one power-factor, it will be satisfactory at all.

High-voltage Oil-switches.—A prominent feature in the illustrations of the high-voltage sub-stations, both indoor and outdoor, in the preceding section is furnished by the massive single-pole oil-switches, which take the place of the more modest appliances used for lower voltage work. The illustrations give a good idea of the general appearance of these switches, the details of which, as may well be supposed, differ widely. Some of them are hand-operated, others are remote controlled, and can be operated automatically by reverse-current relays or other devices as necessity arises, the requisite energy being either electric or pneumatic.

Without attempting to deal with all these varieties, we give in Figs. 1,207 and 1,208 details of a hand-operated switch which represents standard practice with the Pacific Gas and Electric Company, which controls eleven hydro-electric generating stations, which in 1910 had an aggregate capacity of 65,000 kilowatts, with transmission lines 1,020 miles in length. In the illustrations, Fig. 1,207 is a plan of the switch with the top removed from the left-hand half, whilst Fig. 1,208 is a sectional elevation through the line A B in Fig. 1,207. The details are given very fully in the illustrations, and further description is scarcely necessary, but it may be noted that the switch is a four-break knife type of switch. The two bridging pieces are mounted $4\frac{3}{4}$ inches apart on a substantial porcelain insulator on the central spindle, and the knife contacts are hatchet-shaped. The fixed contact jaws are carried on well-insulated spindles, and the leads pass out through long and thick-ribbed porcelain insulators of the type described elsewhere. As is usual in this kind of apparatus, they are raked outwards so that the exposed terminals in the air are 27 inches apart, whilst the opposite contacts inside are less than 18 inches apart. The oil level is well

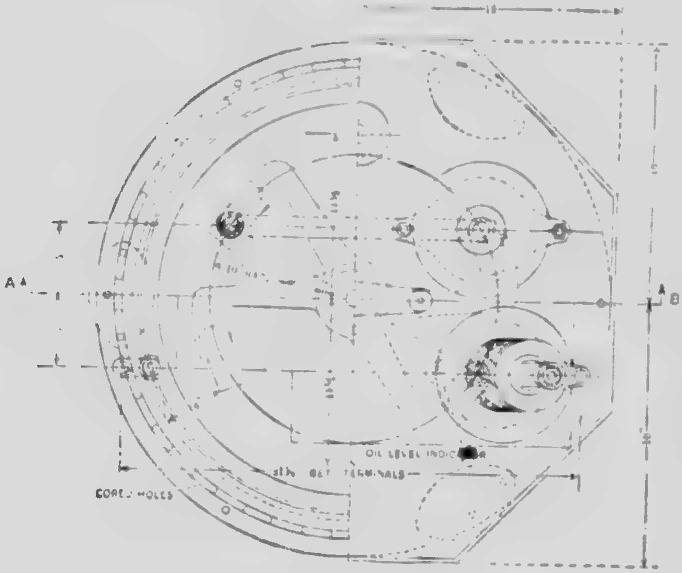
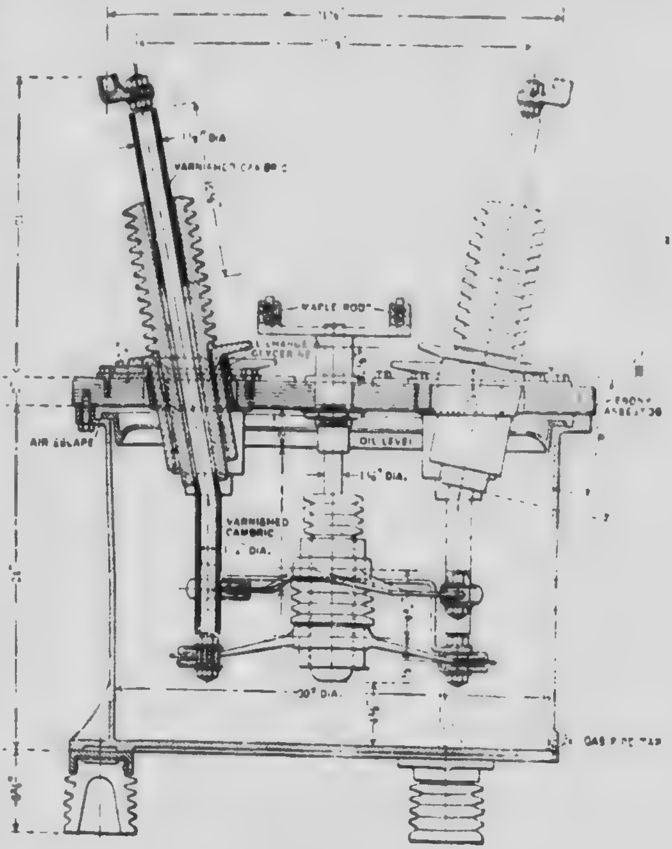


Fig. 1,207.—Plan of High-voltage Switch.

above the contacts, and is maintained constant at all positions of the moving parts, and there is no inflammable material in danger of taking fire from leakage or from an arc. The whole switch is insulated from the ground by ribbed porcelain insulating columns, 5¾ inches high, which afford protection against breakdowns due to surges or other high-voltage disturbances when the switch is open. Lastly, the switch is smaller than many of those illustrated above, as it occupies a ground space only 3 feet square, and its height to the top of the terminals is less than 53 inches. The highest voltage used on the lines on which these switches are installed is 100,000 volts.



SECTION ON A-B

Fig. 1,293.—Sectional Elevation of High-voltage Swit .

II.—KINETIC TRANSFORMER SUB-STATIONS

In all cases where the sub-station is required to do more than transform the voltage or the voltage and phase on an alternate-current system, it is (apart from the use of rectifiers) necessary to install running machinery which cannot well be handled out of doors, and for which, therefore, an indoor sub-station has to be provided. Such a sub-station is most conveniently referred to as a kinetic transformer sub-station, though it may in addition—and often does—contain other transforming apparatus which is not kinetic.

The various types of kinetic transformers have already been fully described and the principles of their action explained. For our present purpose the sub-stations in which they are used may be conveniently divided into the following three classes:

(*a*) Motor Generator (coupled plant) sub-stations using either
  (i.) synchronous motors, or
  (ii.) induction motors,
(*b*) Rotary converter sub-stations,
(*c*) Motor converter sub-stations,

and we propose to deal with them in this order.

The choice of a site for a kinetic transformer sub-station is free from many of the difficulties which beset the corresponding choice (*see* page 433) for a generating station. To begin with, many modern generating stations require a sub-station, either on the premises or close at hand, for, amongst others, two purposes. One is to supply the station itself with the necessary current for its own lighting and the power required by small auxiliary plants, since oftentimes the bulk of the power as generated is not suitable for such purposes. The other object is to transform large quantities of the power generated into a suitable form for a particular system of transmission. This latter is often the reverse of the operation required in distant sub-stations of the system, but the machinery and apparatus required is often similar if not identical. For our present purpose, therefore, we may disregard the difference between generating station sub-stations and outlying sub-stations so far as general plan and lay-out are concerned, though the purpose of any particular sub-station must always be clearly realised.

The choice of a site for an outlying sub-station is part of the general plan of transmission and distribution, and is determined in accordance with such general plan. Expensive sites can easily be avoided, for the sub-station need not be placed in a prominent position in a main thoroughfare. The cheapest back site within a given radius will usually be found to fulfil all necessary requirements.

Motor Generator Sub-stations.—A good example of a sub-station attached to a generating station is furnished at the Bradford generating station, which we have described elsewhere (*see* pages 446 to 449). In one corner of the plan (Fig. 462), and adjoining No. 2 Engine Room, will be found a rectangle marked "E. H. T. Room," the letters "E. H. T." meaning, as explained elsewhere, "Extra High Tension," which is the official designation in England of a voltage as low as 6,500 volts. The station contains a large quantity of continuous-current generating plant and three turbo-alternators, but it has been found desirable to be able to transform some of the continuous-current power at 400 to 500 volts into alternate-current power at 6,500 volts to supplement for transmission purposes the output of the alternators.

The interior of this E. H. T. room is shown in Fig. 1,299, in which the floor is occupied by three Westinghouse motor-generator sets. The capacity of each set is 500 *k*V.A., the motors being the large continuous-current machines which take power at 400 to 500 volts and drive the directly coupled alternators at 300 R.P.M., these alternators having a full-load three-phase output of 500 *k*V.A. at 6,000 to 6,500 volts and 50 periods. The C.C. motor is mainly shunt excited, but has a compound series winding, which acts differentially when the machine is running as a motor, and tends to limit the variation of speed. If the set were working in the reverse direction from A.C. to C.C., this winding would act as a compound winding, helping the field and keeping up the voltage on heavy loads. At the far end of the shaft there is a small compound wound C.C. machine which acts as an exciter supplying the current for the shunt field of the motor. This machine has a weakly saturated field, and is therefore very sensitive to variations of speed. If the speed falls owing to a drop in the C.C. supply voltage, the field of the C.C. motor receives appreciably

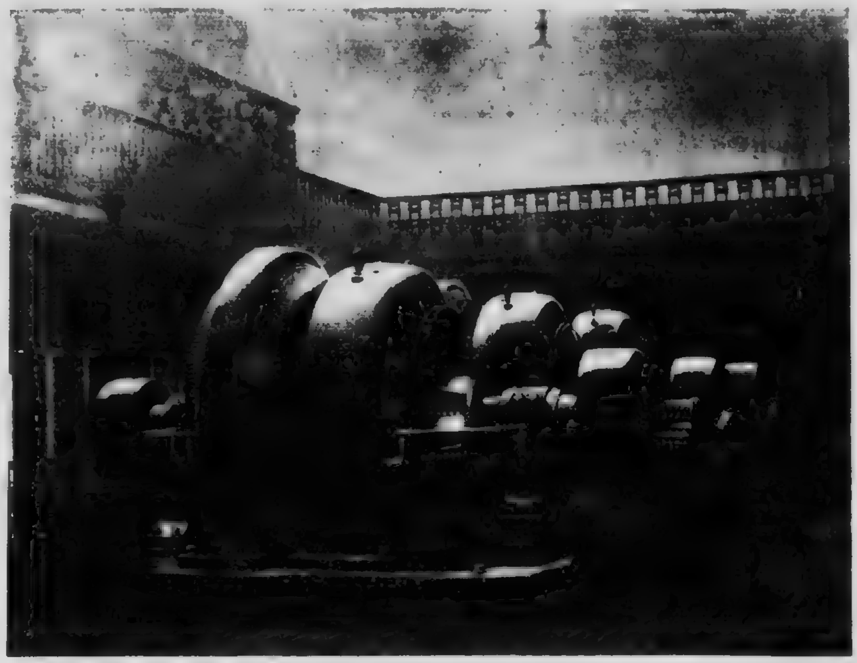


Fig. 1,299.—Bradford 1,500 *k*V.A. Continuous and Alternate-current Sub-station.

less current and is weakened, and thus the variation of speed becomes less than it would be if the field excitation were constant or varied proportionately with the supply voltage only. The large C.C. machine on the near end of the shaft is a booster intended to raise the voltage on the brushes of the large motor when the set is being operated at 470 volts, the somewhat low voltage of the lighting busbars. By these methods the A.C. voltage is kept fairly constant, whichever of the different C.C. busbar voltages is used to supply power to the motor.

The switchboards for these motor generators and the turbo-alternators are in the galleries seen in Fig. 1,299, but it is not possible to pick out the details. The control panels for the motors are, however, on the floor of the room.

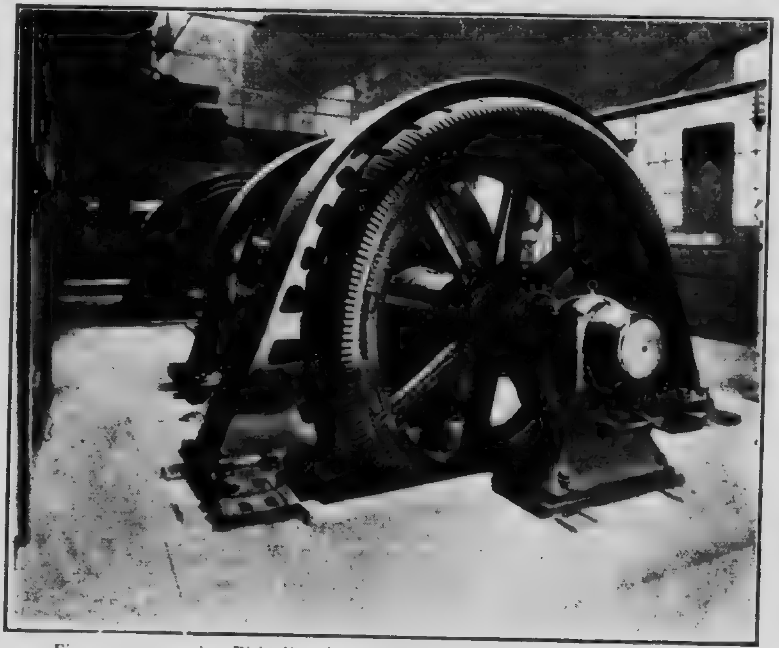


Fig. 1,300.—1,500 Kw. Dick, Kerr Induction Motor Generator Set in London Electric Tramways Substation.

Although many of them date back to the year 1909 or earlier, some reference to the sub-stations of the London County Council tramways in London may not only be of interest to readers who are Londoners, but to others because of their position in the metropolis of the empire. Unlike the electric lighting of London, which has been entrusted to many and diverse corporations, the supply of electric power for the tramways is in the hands of the supreme municipal authority, the London County Council.

There is, therefore, only one generating station, to which reference is made elsewhere, and which is at Greenwich, on the extreme east of the area. At this station three-phase power at 6,000 volts between phases and at 25 ∿ is generated and transmitted by underground cables to twenty-three sub-stations thirteen on the south and ten on the north side of the river. At these sub-stations it is transformed by kinetic transformers, assisted where necessary by static transformers, to continuous-current power at 550 volts. The original equipment * of these stations was:

17	300-*k*w. synchronous motor generators
6	500-*k*w. ,, ,,
58	500-*k*w. induction motor generators
2	1,500-*k*w. ,, ,,
2	1,500-*k*w. rotary converters

The induction motor of one of the 1,500-*k*w. induction motor generators is shown in Fig. 1,300, and the continuous-current dynamo can also be partly seen. The set which was built by Messrs. Dick, Kerr and Co., Limited, runs at 137 R.P.M., and therefore the induction motor has twenty poles and runs about 8 per cent. below synchronous speed. The rotor is wound, and slip rings are provided for the insertion of a water resistance at starting, the full busbar voltage being switched on to the stator at starting. The resistance, as explained elsewhere, is gradually removed as the motor comes up to speed.

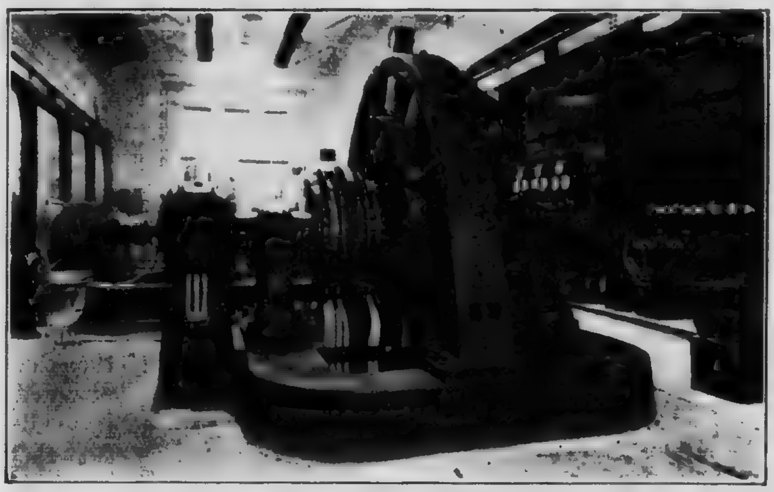


Fig. 1,301. 1,500-*k*w. Dick, Kerr Rotary Converter in London Electric Tramways Sub-station

One of the 1,500-*k*w. rotary converters, also built by Messrs. Dick,

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* Most of the following data are taken from a paper by Mr. J. H. Rider, read before the Institution of Electrical Engineers on March 25th, [illegible].

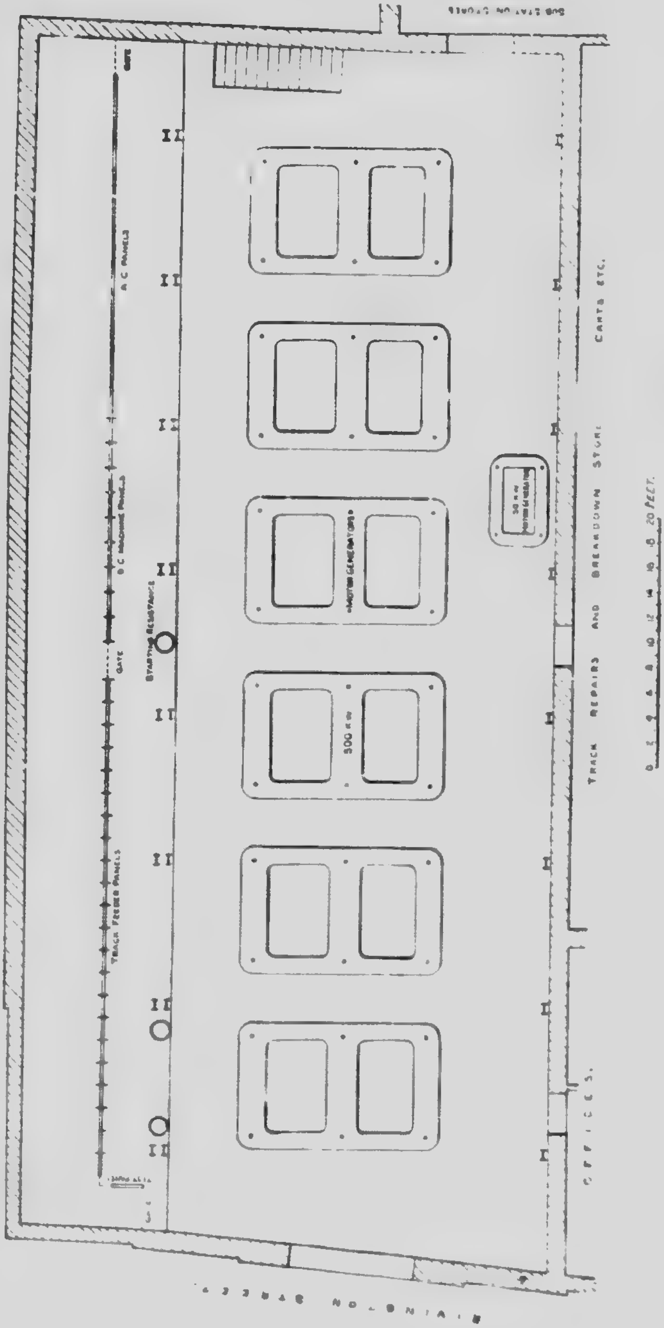

Fig. 1,302.—Motor Generator Sub-station, London County Council Tramways

Kerr and Co., is shown in Fig. 1,301. The machine is a 12-pole machine running at the synchronous speed of 250 R.P.M., being supplied with six-phase currents supplied from three-phase transformers connected as shown in Fig. 1,013. A small three-phase induction starting motor, with its squirrel-cage rotor on an extension of the shaft, is mounted on a pedestal outside the bedplate. The method of starting is as described in the chapter on rotary converters.

The plan of one of these sub-stations may be used to illustrate the general lay-out of a modern motor generator sub-station receiving electric A.C. power at a moderately high voltage and delivering C.C. power at a voltage suitable for traction or factory working. The plan of the machine-room of the Shoreditch sub-station of the London County Council electric tramways is therefore given in Fig. 1,302. The plan shows a range of six 500-*kw*. motor generators in a single row occupying the length of the room with a small 50-*kw*. motor generator at the side for special work, such as starting a big machine from the C.C. side if the station be "dead." The switchboard, which is of the panel type, runs along the whole length of the station, the A.C. receiving panels being on the right; next to them

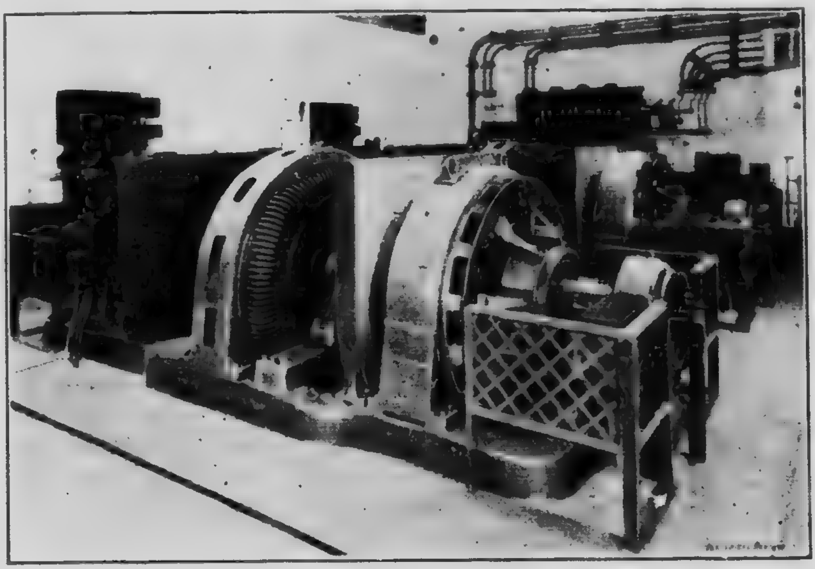

Fig. 1,303.—Chicago, Milwauk[illegible] St. Paul Railway Sub-station.

are the C.C. machine panels, and [illegible] C.C. track-feeder panels to control the outgoing power are on the left, occupying about half the length of the board. There is also a testing panel on the extreme left. A few starting resistances are placed in front of the machines between them and the board, but, compared with a generating station, the whole plan is extremely simple, owing to the absence of the engines and their auxiliary plant. The particular station illustrated is what is known as a basement sub-station; in other words, the actual high-voltage switchgear is in the basement below the switchboard, as illustrated elsewhere (*see* page 1266), and the whole of the remainder of the basement is available for the various incoming, outgoing, and inter-connecting cables which, as there is ample space, are very accessible and can be run in the most convenient manner. The other type is the "gallery" type, in which the high-voltage switchgear is carried on a gallery above the switchboard. It is cheaper to build, and the high-voltage gear is better lighted.

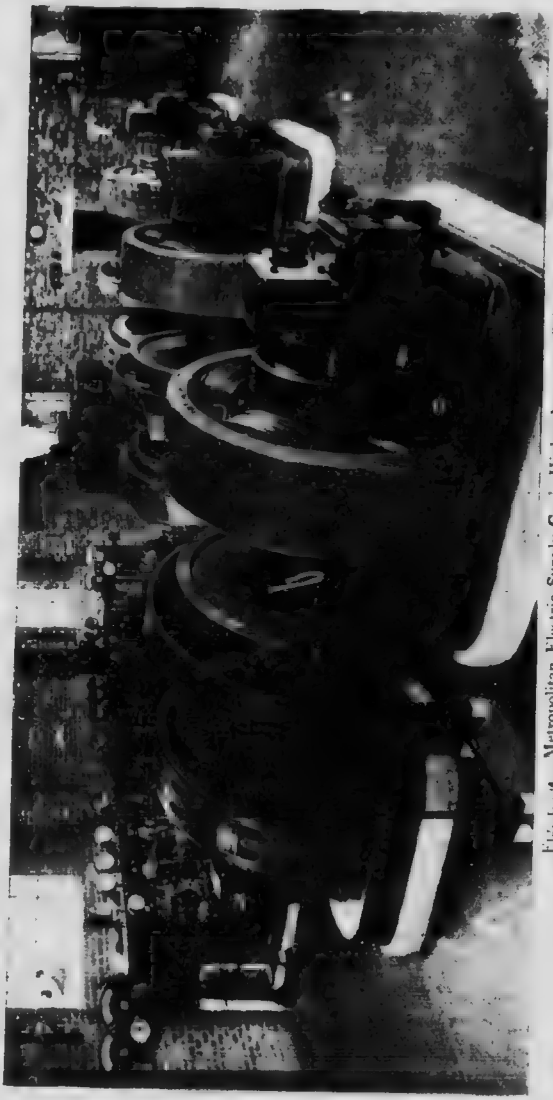
Fig. 1,304. Metropolitan Electric Supply Co.'s High-voltage Co.'s Sub-station.

The offices, stores, etc., of the sub-station are not shown in detail, as they most frequently depend upon the exigencies of the site as determined by the land available. Their positions, however, are indicated on the diagram, at the bottom of which there is a scale showing that the machine-room is roughly 97 feet long by 44 feet wide, including the space necessary for the switchboards. As already indicated, the station capacity is 3,000 kilowatts, and it is interesting to note that the land, buildings, and equipment cost £30,720, which is £10·24 per kilowatt.

As an example of a different kind of practice from America, Fig. 1,303 shows one of fourteen motor generator sub-stations on the Chicago, Milwaukee and St. Paul Railway. In this case the A.C. transmission voltage of 100,000 volts has been stepped down to 2,300 volts in a neighbouring high-voltage sub-station, and the energy enters the sub-station illustrated as A.C. energy at this lowered voltage. This energy operates a 2,000-*k*w.

synchronous motor at the extreme left in the foreground of Fig. 1,303. On the same shaft are the armatures of two 1,000-*kw*. 1,500-volt C.C. dynamos permanently coupled in series to supply 3,000-volt continuous current to the overhead conductor of the railway for distribution to the locomotives. There are insulating shields and couplings between the three machines of the set, whose fields are separately excited by two small C.C. dynamos mounted on the shaft.

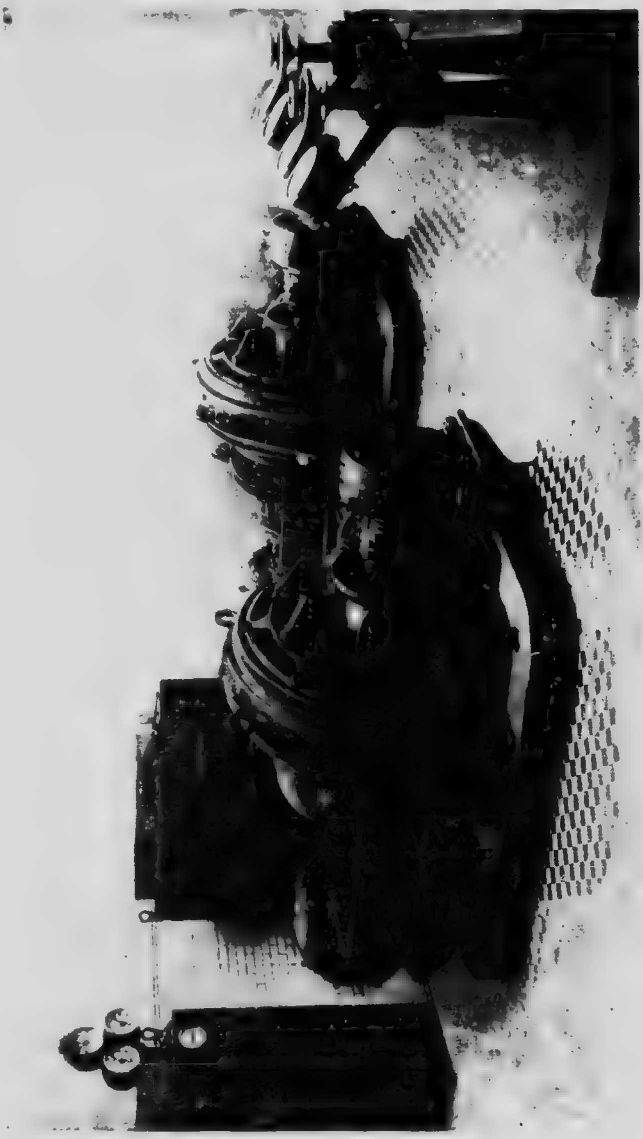

Fig. 1,304. Burslem Rotary Converter Sub-station.

In this country, motor generator sets for converting A.C. power into C.C. power have been practically superseded by rotary and motor converters.

Continuous-current Sets.—There is one type of sub-station in which the necessary conversion from high to low voltage is necessarily entrusted to motor generators.

and that is in the high-voltage C.C. system of transmission described on pages 1190 to 1196. In this system the line potential may be anything up to 37,500 volts above or below the earth potential, and must not be handled by ordinary consumers. It is, therefore, supplied to a properly insulated C.C. motor driving a generator of any type necessary for the service of the particular sub-station.

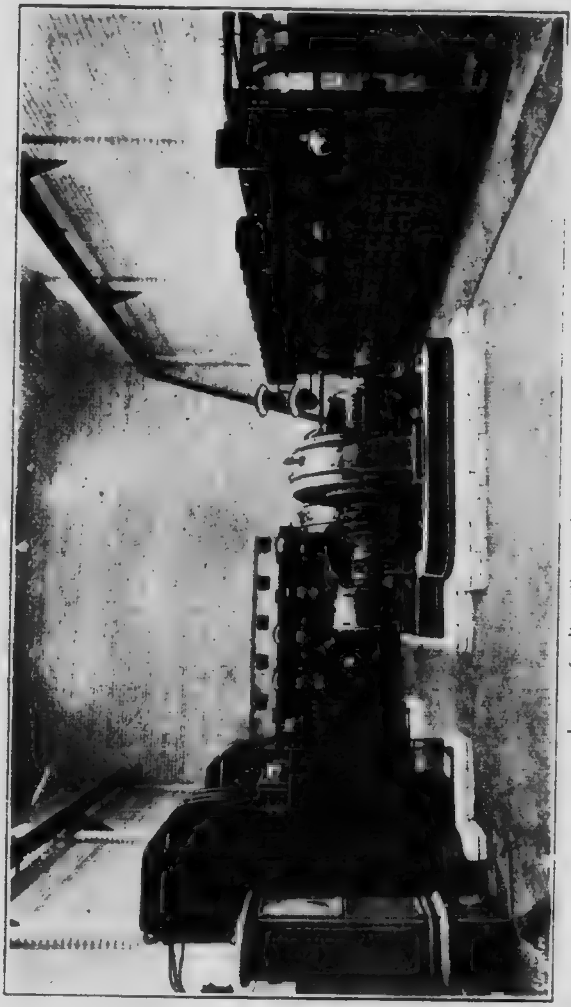

Fig. 1,306.—Port Glasgow Rotary Converter Sub-station

One of these sub-stations, as installed on the high-voltage C.C. system of the Metropolitan Electric Supply Company, is shown in Fig. 1,304, which is taken from Mr. Highfield's paper previously referred to (*see* page 1191). The machine in the foreground at the right-hand end of the shaft is a 250-*k*W. C.C. motor, taking power from the high-voltage mains. This machine stands upon an insulating foundation, and has an insulating coupling connecting it mechanically to the generator at the far end of the shaft. The generator is a three-phase alternator, supplying current at 3,000 volts and 50 ∿. The speed of each machine is 500 R.P.M., which is higher than the speed of the generators in the power station. The switching arrangements on the high-voltage side are as simple as those at the power-house (*see* page 1193).

Rotary Converter Sub-stations.—As the kinetic transformers in these sub-stations must necessarily, as explained elsewhere, be supplied with low-voltage alternating currents in addition to these transformers, step-down static transformers are also required.

An illustration of a rotary converter sub-station is given in Fig. 1,305, which shows the interior of the Burslem sub-station, which receives power from the Stoke municipal electric system. The Westinghouse rotary converters, which are compound wound with commutating poles, have a capacity of 600 kilowatts each, and are used with the static transformers seen in the background, which receive three-phase alternating currents at 6,000 to 6,600 volts and 50 periods, which the plant transforms to continuous currents at 460 to 495, 470 to 505, and 490 to 525 volts, the three ranges being obtained by tappings on the high-voltage side of the transformer. The intermediate regulation and the power-factor control are obtained from the A.C. booster, whose action has been explained at page 979 and elsewhere, and from the field rheostats which are operated from the pillars seen on the right-hand side of the figure. One of the handwheels at the top of the pillar regulates the booster field and the other the shunt field of the exciter referred to below. The instruments are an ammeter for measuring the field current in the shunt winding of the rotary and a voltmeter with a two-way switch for reading either the voltage of the C.C. busbars or the voltage of the exciter. The change-over switch on the front of the pillar is to allow the rotary to be started by exciting it from the C.C. busbars; with the switch in the running position, the exciting current is taken from the exciter.

Fig. 1,307.—Sub-station in a Shipbuilding Yard.

The rotaries are supplied with six-phase currents from the transformers, and can be started as explained elsewhere from the alternating current side by the induction motor method given on pages 998 and 1001, and by means of the squirrel-cage starting motor on the A.C. end of the shaft. One of the A.C. panels is shown behind the near machine. It carries a throw-over switch for the starting motor and a low-voltage synchronising switch. The instrument on the panel is a frequency meter; above it are two voltmeters for the supply side and the rotary side respectively, and above these a rotary synchroscope such as has been described elsewhere. The rotaries are designed for inverted running, that is, for being driven from the C.C. side to supply power to the A.C. mains. To work smoothly in this way it is found desirable to use a direct-coupled exciter, which can control the speed and supply the increased excitation current necessary to counteract the influence of the heavy demagnetising currents in the armature. In bringing a machine into action it is necessary that the voltage, the frequency, and the phase should all be correctly adjusted. The instruments for this purpose are mounted on the A.C. panel shown.

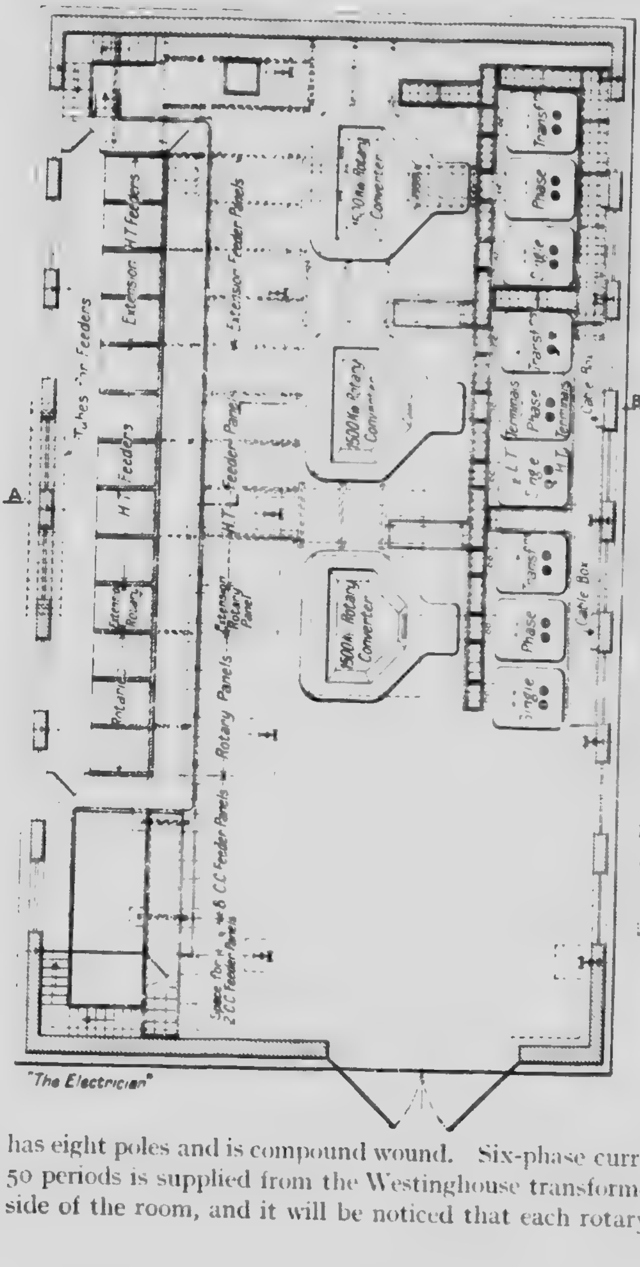

Fig. 1,306.- Plan of a London and South Western Railway Rotary Transformer Sub-station.

A good idea of a modern rotary converter sub-station can be obtained from Fig. 1,306, which depicts the interior of a Port Glasgow sub-station under the Greenock Corporation electricity department. In the middle of the room can be seen one of the Westinghouse rotaries with another almost hidden behind it. These are each of 500 *k*V.A. capacity, and are of the self-synchronising type referred to on page 1,000. Each has eight poles and is compound wound. Six-phase current at 185 volts and 50 periods is supplied from the Westinghouse transformers on the left-hand side of the room, and it will be noticed that each rotary has its own transformer and regulating resistance. The plant has an overload capacity of 50 per cent. for three minutes and the full-load over-all efficiency is 92 per cent. The supply voltage from the Greenock generating station is 10,500 volts, the current being carried by two three-core, 0·1 sq. in. cables which loop into alternate sub-stations.

At the far end of the room (Fig. 1,306) can be seen the high-voltage switchboard, and on the right-hand side the low-voltage distributing feeder board with the c.c. panels for the rotary. The switchgear was manufactured and installed by the British Thomson-Houston Company.

A view of a shipbuilding yard sub-station on the same system is given in Fig. 1,307, which shows the sub-station in the yard of Messrs. Wm. Hamilton and Co. Here also there is installed a 500-*kv.a.* rotary converter similar to those shown in Fig. 1,306, the only difference being that the c.c. voltage is 4[illegible] volts. This sub-station has taken the place of generating plant which had been in use in the yard for many years. The other chief shipbuilding firms in Port Glasgow have also replaced their generating stations either by sub-stations drawing their power from the Greenock mains, or by connecting their plant to the c.c. mains from the nearest public sub-station. The whole development, which is as recent as the year 1914, is a good example of the replacement of small private installations of generating plant by the supply of electric power from a central generating station. The capacity of the generating station in this instance was, in 1915, 11,300 kilowatts, and extensions were still being made.

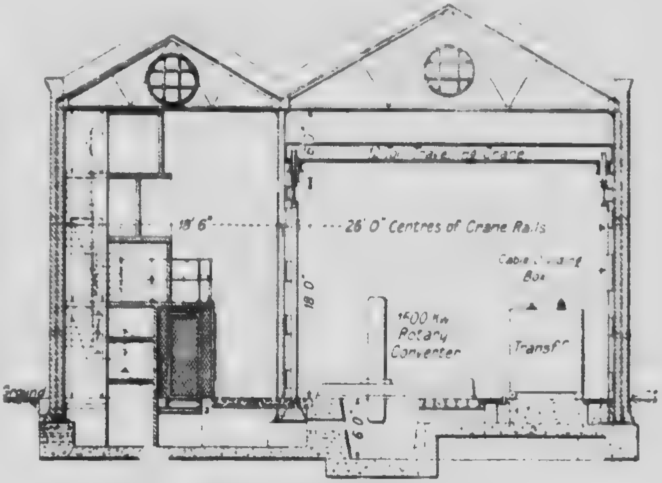

Fig. 1,309.—Sectional Elevation at A, B of Fig. 1,308.

The kinetic transformer sub-stations erected for the recent electrification of the London and South Western Railway's suburban system are also of the rotary converter type. As explained elsewhere, these sub-stations are supplied with three-phase A.C. power at 11,000 volts and 25 ~, which is to be transformed into C.C. power.

The nine sub-stations on this system are practically identical, differing only in the number of machines installed, the general plan being as shown in Fig. 1,308.* A cross-sectionof a station is given in Fig. 1,309. The step-down transformers for each rotary consist of a bank of three separate single-phase transformers, with their primaries "mesh" connected and supplied from a three-phasecable through a dividing box placed immediately behind the bank. Most of the rotaries have a capacity of 1,500 *k*V.A., and for each of these three 550-*k*V.A. single-phase transformers are supplied. Each transformer is wound for a step-down ratio of 10,750 to 445 volts, with primary tappings 2½ and 5 per cent. below and above the normal. Two banks of these transformers are shown in Fig. 1,310. They are Berry transformers, supplied by the British Electric Transformer Company, and it will be noticed that the oil tanks are fitted

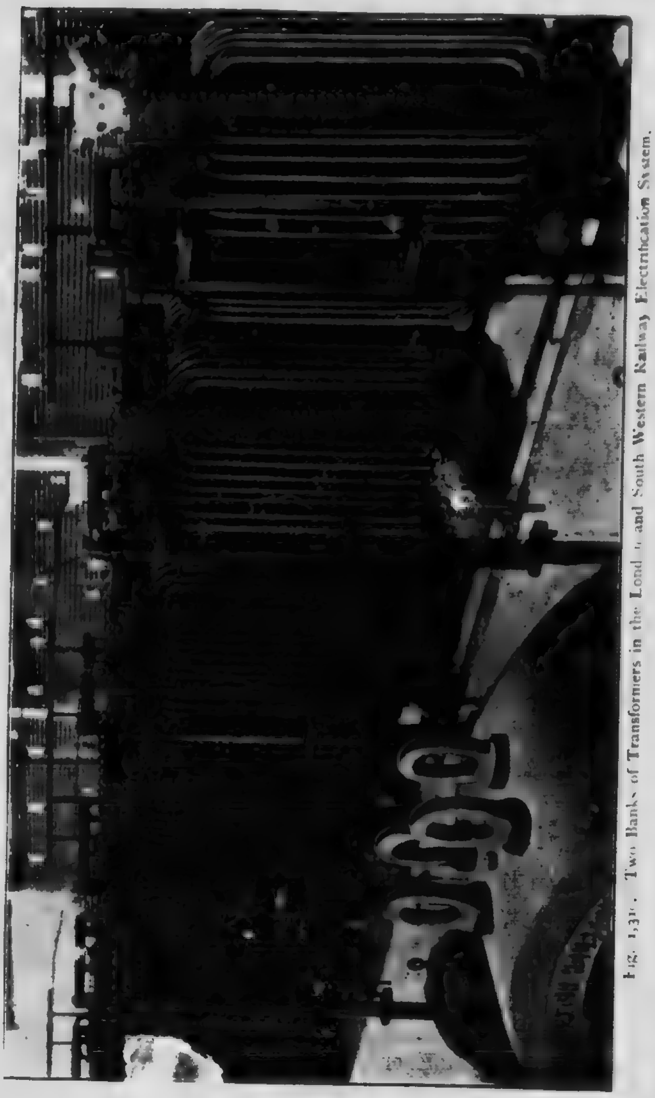

Fig. 1,310. Two Banks of Transformers in the London and South Western Railway Electrification System.

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* This and the following figures are taken from an article in *The Electrician* for November 15, 1915.

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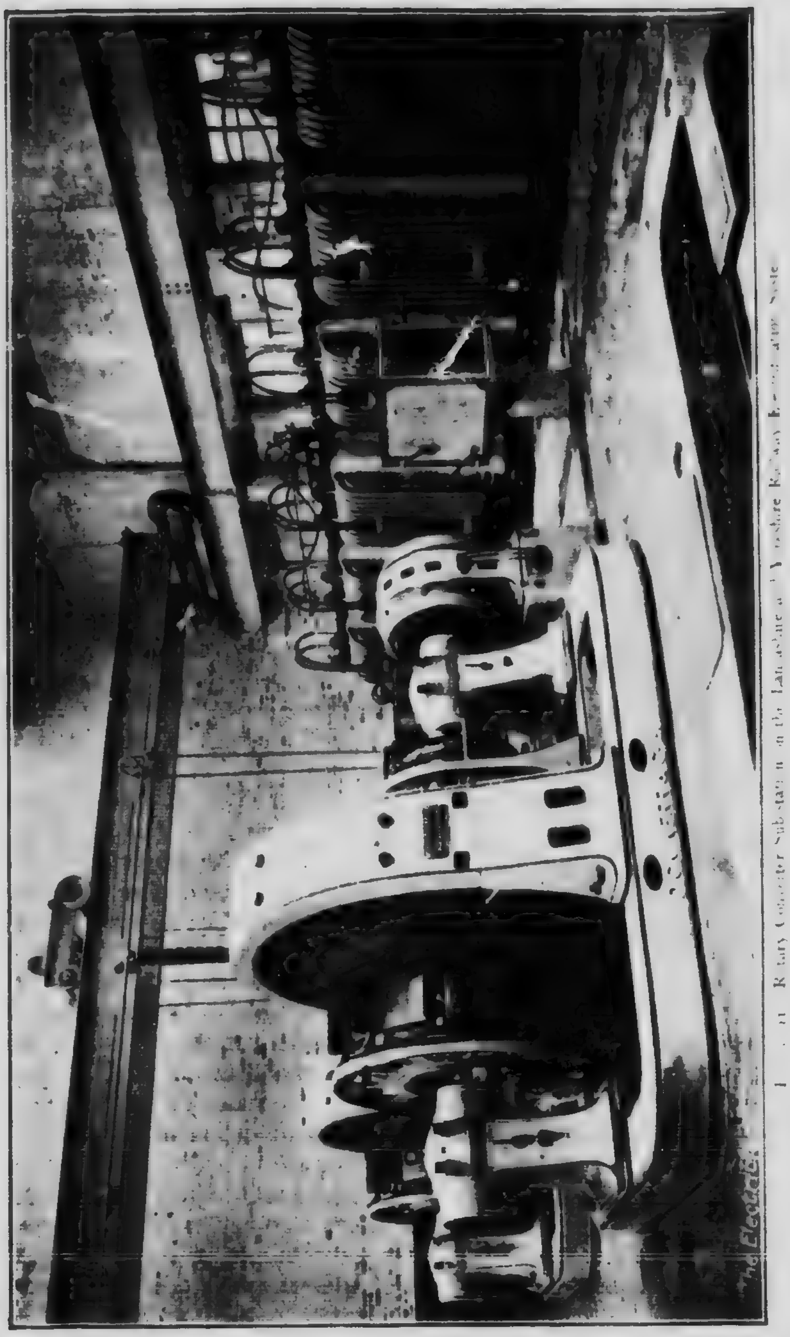

Fig. 11. Rotary Converter Sub-station on the Lancashire and Yorkshire Railway Electric [illegible]

with external radiating and circulating pipes of the kind already described (*see* pages 913 and 922). In four of the smaller sub-stations the rotaries are only of 1,000 *kv.a.* with correspondingly smaller transformers.

The rotaries were supplied by the British Thomson-Houston Company, and are similar to the machine illustrated and described at pages 977 and 978. They are 10-pole machines running at 300 R.P.M., and are fed with six-phase currents by the static transformers. Each machine is started from the A.C. side by means of a starting motor, whose squirrel-cage rotor is on the main shaft and whose stator has only eight poles, that is, one pair less than the rotary, in order that, notwithstanding the slip, it can run the big machine up to the synchronising speed at which it can fall into step without any special arrangements for synchronising. The method of starting is that described at page 999 (Fig. 1,020). The switchboard is referred to on page 1261 and Fig. 1,306.

As a final illustration of a rotary converter sub-station, Fig. 1,311, from *The Electrician* of January 21, 1916, shows the interior of a sub-station erected for the recent electrification of the Manchester to Bury section of the Lancashire and Yorkshire Railway. This station transforms 6,600-volt three-phase A.C. power at 25 periods to 1,200-volt C.C. power. The rotaries are Dick, Kerr 1,000-*kw.* machines, each supplied by a bank of three 350-*kv.a.* single-phase transformers, which, as in the preceding case, are oil cooled with external circulating and radiating pipes. The illustration also shows the starting pillar for the machine placed just behind the starting motor and between it and the transformers. The method of starting has been described elsewhere.

Motor Converter Sub-stations.—One of the advantages of the motor converter is the simplicity of the starting arrangements from the alternate-current side, so that in a sub-station equipped with these kinetic transformers complications on the switchboard can only be due to conditions of distribution on the continuous-current side. It will be remembered that no step-down transformers with their switchgear are required, and the machines themselves require very little attention when running. It will probably suffice, therefore, if we give only one illustration of a sub-station using them.

The sub-station selected is installed in one of the works of Messrs. Hadfield's, Limited, the well-known steel makers of Sheffield. The interior of the station is shown in Fig. 1,312, in which can be clearly seen three large Peebles motor converters, each rated at 500 kilowatts. The line-voltage at which three-phase power is supplied to the sub-station is 11,000 volts at 50 ∽, and the C.C. voltage is maintained constant at 230 volts. The three switch columns in the foreground contain the starting resistances, which are inserted in the rotor circuit as shown generally in the diagram in Fig. 1,030. One of the switches on each column is the starting switch, and the other the synchronising switch. After the high-voltage stator switch, which is not shown, has been closed, the starting switch is closed, putting in a fixed resistance on the rotor circuits, under which the machine runs up to the synchronous speed, which is shown by the voltmeter at the back of the column. When this is reached the synchronising switch is closed, short-circuiting the added resistance, the rotor itself being afterwards short-circuited by the gear on the shaft

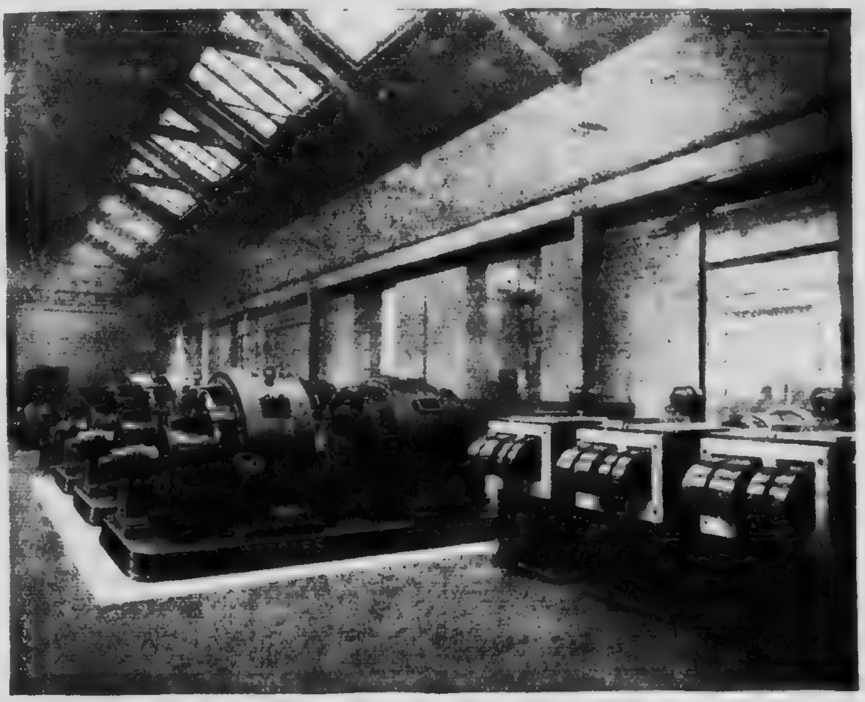

Fig. 1,312.—Motor Converter Sub-station at Messrs. Hadfields, Ltd., Sheffield.

II. (I.)—OPERATION OF KINETIC TRANSFORMER SUB-STATIONS

Some of the most important details in connection with the operations peculiar to kinetic transformer sub-stations have already been fully described in the chapter on kinetic transformers, and these descriptions need not therefore be repeated here. Reference may be made more especially to

(i.) The supply of six-phase current to rotaries (page 986).
(ii.) Starting and paralleling (pages 994 to 1001 and 1012).
(iii.) Voltage regulation of the machines (pages 1001 to 1006).
(iv.) Inverted running of rotaries (pages 1006 to 1008).

As certain other operations of a general character are more conveniently dealt with in a separate section (*see* Section IV. *infra*), there only remain for description here some of the typical forms of switchboards designed for the manipulation of kinetic transformer sub-stations.

Switchboards.—Even in this case the full treatment of the switching arrangements of generating stations already given at pages 518 to 574 makes it unnecessary to devote much space to the details of the switchboards and their accessories here. In the "panel" method of construction of switchboards a fair number of panels, such as "feeder" panels, synchronising panels, generator and motor-control panels, are of the same standard construction for generator station and for sub-station working. A few further illustrations of special types may, however, be of interest.

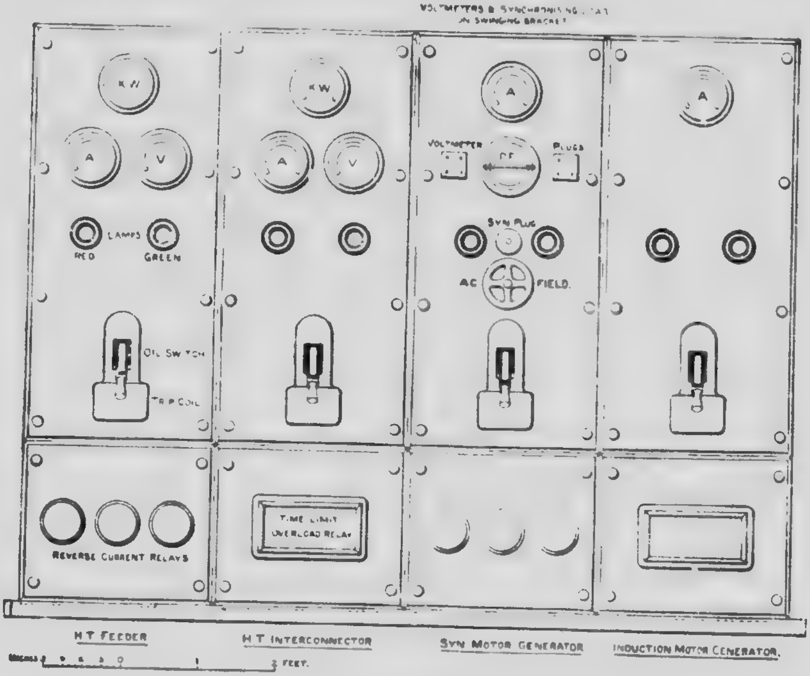

FIG. 1,313.—High-voltage Panels, London County Counc.. Tramways Sub-station.

The panels used in the motor-generator sub-stations of the London County Council electric tramways (*see* page 1252 *ante*) are shown in Fig. 1,313, in which four typical high-voltage panels are ranged side by side. The diagram, if carefully studied in connection with the section referred to, is almost self-explanatory. On the left is a high-voltage feeder panel on which the incoming energy is controlled; K W is a wattmeter indicating the power which is being received; and A and V are an ammeter and a voltmeter operated through instrument transformers. Below are the signal lamps which show whether the oil switch is open or closed, and still further down is the operating handle of the oil switch with its tripping coil. The reverse current relays, one on each of the three-phase mains, are at the bottom of the panel, and the time limit overload relay is at the bottom of the adjacent interconnector panel, which is otherwise similar to the feeder panel. The next panel is for the syn-

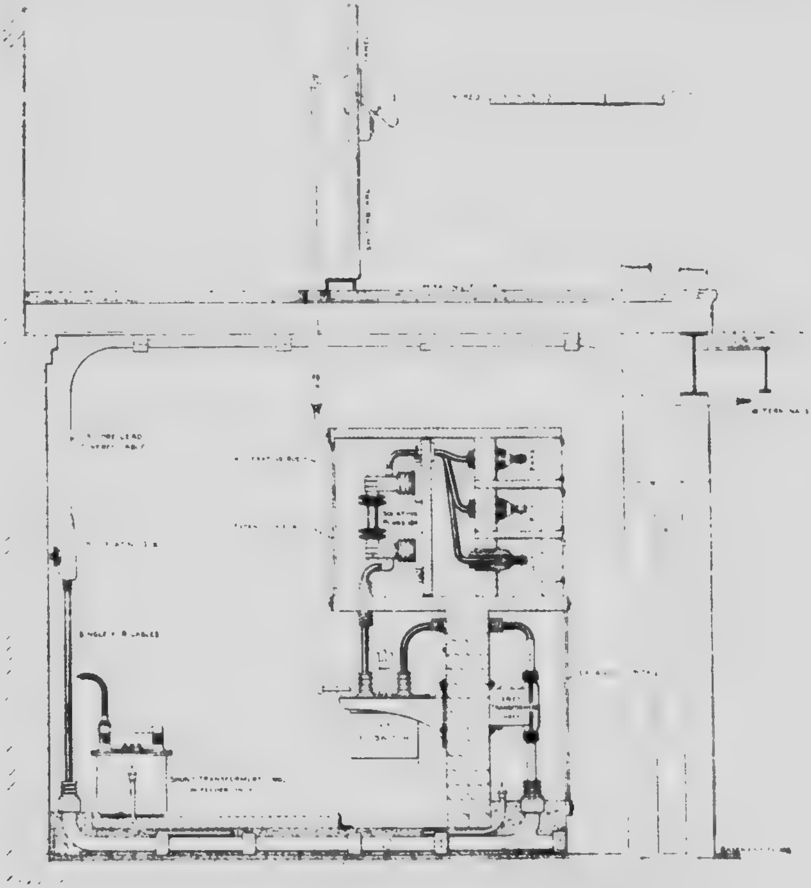

Fig. 631a. Switchgear in Basement of London County Council Sub-station

chronous motor generator, and the last one for an induction motor generator. The last-named is very simple, as the set is started up from the c.c. side on a low-voltage panel and can be thrown on the high-voltage busbars without special synchronising gear. For the synchronous motor generator such gear has to be provided for the motor, which, having been brought up to synchronous speed by the c.c. generator used temporarily as a motor, must have its field excitation properly adjusted and its armature circuits synchronised before the oil switch can be closed. The field excitation is tested by a voltmeter, which is compared with a voltmeter on the incoming mains. These voltmeters are on a swinging bracket in a convenient position on the board, and are brought into circuit by the voltmeter plugs shown. The synchroscope is also on the swinging bracket, and is connected up by the synchronising plug. The small hand-wheel, marked "A.C. field," controls a rheostat in the C.C. circuit of the field magnet of the synchronous motor.

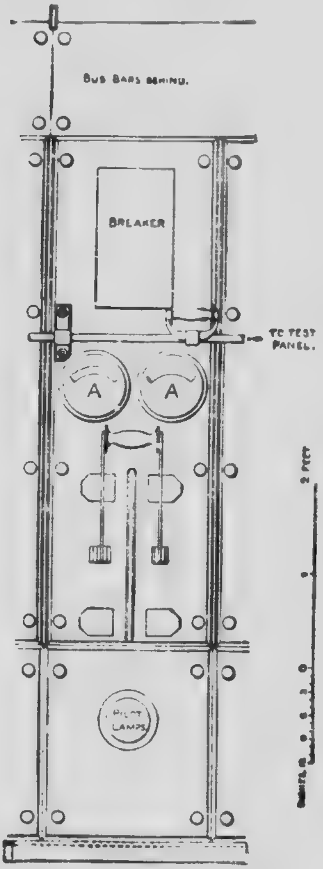

Fig. 1,315.—Low-voltage C.C. Track Feeder Panel.

The positions of the switch-gear, busbars, the current transformers, etc., are given for a "basement" sub-station in Fig. 1,314 which shows the details for the connection of a high-voltage motor to the high-voltage busbars; the dimensions can be obtained approximately from the scale which is given. The operating handle for the oil switch is at the front of the switchboard at H (compare Fig. 1,313), and the various parts and pieces of apparatus are clearly marked on the diagram. The "shunt" transformers are the voltmeter or potential transformers, and the "series" transformers are the ammeter or current transformers. Both these sets of transformers are on the machine side of the oil switch.

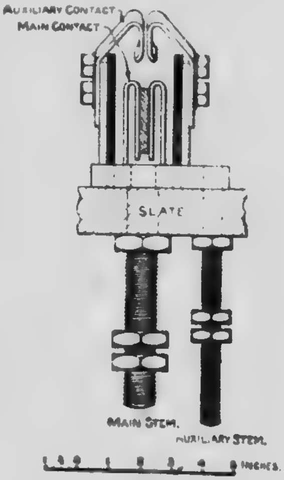

Fig. 1,316.—Testing Contacts of Switch.

A standard low-voltage C.C. track "feeder" panel of the same system, is shown in Fig. 1,315 There is, on the panel, a circuit breaker, two ammeters, a double-pole change-over switch, and a pilot lamp. The system is an underground conduit one, and the circuit breaker is on the + feeder, the negative busbar being permanently earthed through an adjustable water resistance. Both the conductors in the conduit are insulated, and the change-over switch is for the purpose of changing their polarity in the event of a bad earth fault occurring on the + side, which opens the circuit breaker. For this purpose the top and bottom contacts, which are the busbar contacts, are as usual cross-connected. For rapid testing purposes these contacts are double, as shown in Fig. 1,316. When the knife of the switch is driven home it lies

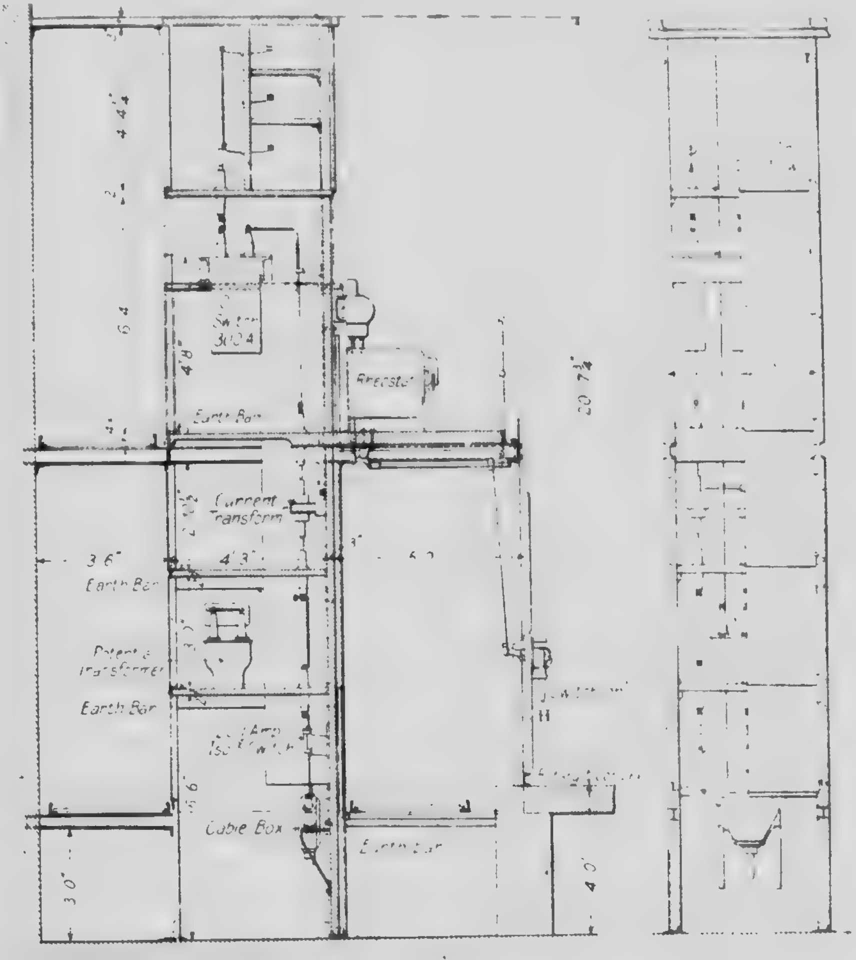

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Fig. [illegible] Fig. [illegible]

Details [illegible] W[illegible]

between the flexible main contacts, and connects the c.c. feeders direct to the busbars; when raised clear of these contacts, but remaining between the upper "auxiliary contacts," the feeder is connected to the busbars through a fixed metallic resistance of 5 ohms and a testing panel on the right of the panel shown in Fig. 1,315, the leads from the different feeder panels passing through the tube shown below the circuit breaker. The ammeters on that panel will then show whether the fault is only a temporary or a permanent one, and if it be the latter whether it is a bad earth fault or not. If not an earth fault, it can further be quickly ascertained whether or not it is a short circuit between the two conductors.

In this connection attention can be directed to the cross-section of the London and South Western Railway sub-station shown in Fig. 1,306 on page 1261, in which, on the left-hand side, there are shown details of the switchboard, of which a plan appears in the corresponding position in Fig. 1,308. The functions of the various panels of the switchboard and their sequence are clearly shown in Fig. 1,308, and it will be noted that the board is practically as long as the station.

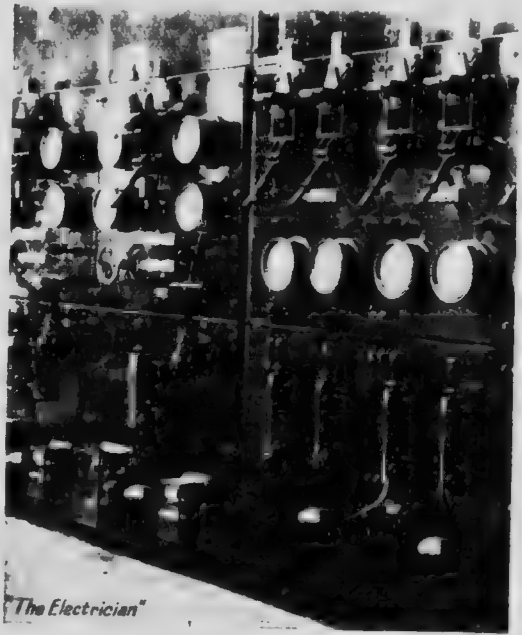
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Fig. 1,316.—Two High-voltage and two c.c. Feeder Panels of London and South Western Railway Switchboard.

An enlarged cross-section of the high-voltage feeder panel of the board is given in Fig. 1,317,* and a diagrammatic front view of the gear and the run of the conductors through the various switching arrangements are given in Fig. 1,318. As each piece of apparatus is clearly marked on these diagrams, the reader will have no difficulty in tracing out the design for himself, and a minute description is therefore unnecessary; the principal dimensions are also clearly marked. The switch-gear is on three levels, with the cable boxes in a low basement, above which, on the ground floor, are the instrument transformers; the oil switches and busbars are on the next floor, whilst the busbar potential transformers and spark gaps, not shown in Fig. 1,317, are on the top floor.

The details of the rotary converter panel are of special interest, and a perspective view of this panel with two adjacent feeder panels is given in Fig. 1,319. There is also given in Fig. 1,320 a diagrammatic elevation of the end of the switchboard, showing details of this panel with two-feeder C.C. panels alongside. The low-voltage switches, circuit breakers, and instruments are mounted on the front of the board, but the high-voltage oil switch is a remote control switch operated mechanically by the handle H (Fig. 1.317); each phase is in a separate tank, the three phases being simultaneously closed or opened by one operation. Returning to the rotary panel (Figs. 1.319 and 1.320), the handle of the oil switch is shown at O I with an A.C. wattmeter below. Above it are the indicating lamps I L, and still higher the low-voltage ammeter A, and the power-factor meter P F M. On the other side are the hand-wheel R H of the field rheostat, and above it a field-current ammeter and a load C.C. ammeter. Below the handwheel there is a single-pole field switch F S, and at the bottom of the panel a C.C. wattmeter. There is at the top of the panel a C.C. circuit breaker C B 3, which will open at 3,000 amperes, and has a reverse-current attachment, whilst on the lower half of the panel there is a single-pole 2,000-ampere switch L S 2. It is interesting to note that the panels are enamelled both back and front, and that all small wiring consists of bare copper wire secured to the panels by porcelain cleats.

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* From *The Electrician* of November 5, 1915.

The negative conductors from the rotaries are taken direct to the main busbar, no switch being interposed, and the negative feeders are taken direct to the negative busbar from the rails. This is an interesting simplification in switching arrangements.

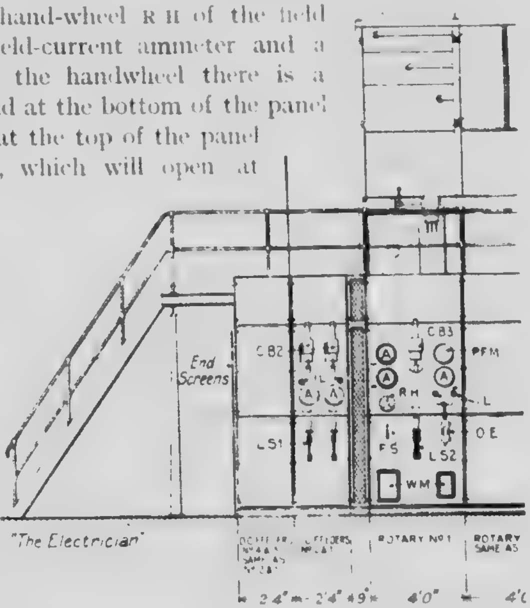

Fig. 1.32[illegible] Part of the London and South Western Railway Switchboard.

III.—SECONDARY BATTERIES IN GENERATING AND SUB-STATIONS

This section, for convenience and conciseness, is not confined to secondary battery sub-stations, but deals briefly with the whole subject of the position and use of secondary batteries in electric power schemes.

The outstanding difference between secondary batteries and other engineering classes of transformers of electrical power and energy is that with a secondary battery all three factors of electrical energy—namely, *current*, *voltage*, and *time*—can be varied as between the input and the output, whereas in the other classes only the first two can be varied (*see* pages 574 *et seq.*, Vol. I.). In other words, secondary batteries are *energy transformers*, whereas the static and kinetic transformers described in Chapters VII. and VIII. (*supra*) are only *power transformers*. The latter can deliver power only during the time in which they are receiving it, whereas secondary batteries store the energy (as *energy of chemical separation*, *see* page 202, Vol. I.), and within the limits of their capacity and efficiency can deliver it as and when required at any future time.

Advantages of Secondary Batteries. A fundamental advantage of the secondary battery is that it does not require the incessant and continuous attention which must be given to running machinery, especially steam- or gas-driven machinery, with their ancillary steam-raising or gas-generating plants. It can therefore take charge of the load on a generating station or a sub-station during the periods of light load without requiring the attendance of a full shift of men, and thus, although as a transformer it is not particularly efficient, its use in many practical cases leads to a reduction of operating charges, notwithstanding the energy wasted in the transformations. Thus, as we have already seen in the chapter on generating stations (pages 532 to 534), the use of a battery for taking the night load in a particular instance in Manchester allowed the running machinery to be shut down from 11.10 P.M. to 6.30 A.M., considerably reducing the wages bill and having other advantages.

Another function of a secondary battery in generating and sub-station working is to take over the "peak" load, and thus to reduce the amount of running machinery to be installed, and to raise the load factor on the machinery in use. In the instance above referred to the maximum load on the generating plant was reduced from 11,000 kilowatts to 8,600 kilowatts, a reduction of 22 per cent., whilst the load factor was increased from 32 per cent. to 43·5 per cent., or by more than one-third. These figures are not at all exceptional, and the conditions cited quite commonly occur in practice.

In manufacturing works the battery has also been found useful in dealing with the peaks of a fluctuating load so often met with, as well as in reducing the running of the generating plant by taking meal-hour loads, night-shift loads, and week-end loads. In a certain case where a thorough test was made, the saving in fuel alone, by so utilising a battery, amounted to nearly 30 per cent., due chiefly to the unavoidable extravagant expenditure of fuel at periods of very light load.

Similarly, on a traction system the secondary battery can be designed to take charge of the load of the late and the early morning traffic, as well as the service of the car-shed during the "off" hours. In fact, the efficient combination would appear to be to put down a generating plant capable of dealing with the average load, and long and steady fluctuations in it, and to arrange for the secondary battery to deal with all short-period fluctuations.

Disadvantages.—To accomplish these and other engineering economies it is, of course, necessary that it should be possible to install batteries which are capable of giving an output comparable with that of, at least, a moderately sized generating plant. For instance, in the Manchester case referred to above the battery for a short time at least was called upon to give 2,400 kilowatts, and unless it could have done this it could not have taken the peak load. As a matter of fact, many batteries having such emergency outputs have been erected, and we shall presently describe one or two of them.

Large Size and Number of Cells.—The details of their construction, however, reveal the outstanding defect of the secondary battery—namely, the large size of the installation compared with the power which it can handle and the energy it can store. This is due to two fundamental characteristics of all secondary cells, the first being the low voltage of individual cells, which is only about two volts in the lead secondary cell, and still less in the Edison cell. The fundamental causes of this low voltage have been fully explained in Vol. I. (*see* pages 151 to 153). The effect is that to obtain even the lowest voltages—say 100 or 200 volts—used in modern engineering work, a great number of cells in series must be taken. The second unfortunate characteristic is the low current density at the surface of the plates, which alone is possible if efficient working is to be obtained. This necessitates that, combined with the low voltages just referred to, very large surfaces must be provided by the plates of the individual cells if the electrical power necessary to accomplish the above-named objects is to be developed. If thus, not only must the cells be many, but also the size of the individual cells large, and consequently their weight heavy, it follows that a secondary battery capable of giving, say, 1,000 kilowatts at 200 or 400 volts for two or three hours only, is a large, massive and expensive installation.

Necessity for Regulation.—Whilst summarising defects there is one other point to which attention must be drawn, and which will become apparent on an inspection of the charge and discharge curves given in Figs. 1,074 to 1,076 (*ante*). This is the serious percentage fluctuations of voltage of individual cells (at constant current) between the lowest voltage permissible at the end of a discharge and the highest voltage necessary to complete the period of charge. Such fluctuations of voltage, which are often simultaneously undergone by all the cells in series, necessitate some regulating device, which should preferably be automatic, by which the voltage of supply and distribution can be regulated and kept constant. Two such methods of regulation have been each widely employed—namely: (i.) the alteration of the number of cells in the battery by cutting in or out the "*end cells*"; and (ii.) the use of positive and negative "boosters," either automatic or hand regulated. Details of these methods will be given after the description of a few typical batteries.

Batteries in Sub-stations.—In order that our readers may form some idea of what such secondary batteries are like in practice we select from a large number of available examples a few cases which may be regarded as typical.

The first is a comparatively small battery, but very nicely installed, in the cocoa works of Messrs. Rowntree and Co., at York. The generating plant, partly steam-driven and partly gas-driven, has an output of about 1,600 kilowatts, and works at 23[illegible] volts on a power and a lighting load. The battery shown in Fig. 1,321 consists of 112 "**D.P.**" cells, and the maximum discharge rate is 800 amperes for one hour down to a final pressure of 193 volts, or 1·72 volts per cell. The regulator is an automatic reversible booster, which is necessarily in an adjoining room. The cells are in wooden boxes, arranged in four rows, all on the same level, and the method of mounting should be noted. The boxes rest each upon four insulators on longitudinal bearers, which in their turn rest upon double transverse bearers, the lower of which rests on the floor and supports the upper on insulators. The series connectors between adjacent rows may also be noted. For reasons given elsewhere the battery is in a special room reserved for it. In this case the room is pleasantly designed.

The next example is one in which the demands on the battery by fluctuation of load are probably much more severe, as it is installed in a steel works using about two hundred motors, aggregating 4,000 B.H.P. at full load, and mostly series wound, which, it may be recalled, leads to heavy starting currents. The works are those of Messrs. David Colville and Sons, Limited, at Dalzell. The battery room, shown in Fig. 1,322, contains 114 cells of the "Chloride" accumulator type, having a discharge capacity of 1,100 amperes for one hour, the regulator being an Entz booster (*see* page 1291). These cells are also in wooden boxes; each consists of twenty-nine plates of the chloride type, each cell weighing about 1,180 lb., making the weight of the battery over 60 tons. The individual cells rest upon insulators, and, as in the previous case, the cross bearers are also insulated. The nearest cell in the picture is the —ve end cell, and the very substantial leads which carry the current to and from the battery should be noted rising vertically from the substantial connector bar.

The next example selected is connected with traction work, and is a view in Fig. 1,323 of a battery room on the Liverpool Overhead Railway system. In this room there are two 750 *k*w.-hour batteries of the well-known E. P. S. type. These batteries are used as equalisers on the fluctuating load inseparable in railway work. Each battery consists of 248 cells, and each cell contains twenty-seven plates, of which the 13 +ve are of the Planté type described elsewhere, each plate weighing 21 lb., and the 14 —ve are of the E. P. S. lattice type, each weighing 14 lb.

The plates alone in each cell therefore weigh 400 lb. or over 4 cwt.; they are supported by ¼-inch glass slabs, and are separated by ½-inch wood

Fig. 1,021. D. P. Battery Sub-station [illegible] Works.

dowels through slots in which wood sheet separators are threaded. Th complete cell filled with acid weighs 660 lb., and the two batteries ther

A Secondary Battery Installed in a Steel Works [illegible] weigh over 210 tons without taking account of the weight of the supports. The batteries are charged daily between 7 P.M. and 6.30 A.M.

[illegible]

each battery being charged separately by means of an auxiliary boost driven off the busbars, and the normal charging rate being 260 ampere between a minimum of 175 and a maximum of 390 amperes. They ar discharged in parallel with the generators, the regulation being effecte by 9 end-cells in groups of 1, 2, 3, and 3. This method of regulation i probably now replaced by an automatic reversible booster. The discharg current varies from 650 amperes, at the one-hour rate, to 150 amperes, a the ten-hour rate, the capacity of each battery at the latter rate bein 1,500 ampere-hours with a voltage drop down to 1·8 volts per cell.

A Large Battery Sub-station.—We shall conclude this sectio with a brief description of the battery sub-station and the battery erected and installed for the Metropolitan Electric Supply Company, in Eagl Street, Holborn, London, which, when installed, was one of the largest battery sub-stations, from the point of view of output, in this country.

The battery, shown in Fig. 1,324, was supplied by the Chloride Electric Storage Company, whose productions have been referred to in Chapter IX. It consists of 110 cells, each containing 53 plates, 26 +ve and 27 —ve, each plate being $40\frac{3}{8}$ in. long and $16\frac{1}{4}$ in. wide, the +ves being $\frac{7}{16}$ in. and the —ves $\frac{5}{16}$ in. thick. Each + plate weighs 90 lb., and the discharge surface of the +ve for each cell is very nearly 270 sq. ft. The rate of discharge is 1,200 amperes for ten hours or 6,000 amperes for one hour. The current density is therefore 4·3 amperes per square foot at the ten-hour rate and 22·2 amperes per square foot at the one-hour rate. The battery can also stand a discharge of 15,000 amperes momentarily and 12,000 amperes for one minute, the latter giving the high current density of 44·4 amperes per square foot. The —ve plates weigh 41 lb. each, except the end plates, which only weigh 34 lb., and the total weight of plates in each cell is therefore 3,452 lb. or over $1\frac{1}{2}$ tons; the weight of each cell complete with acid is therefore 6,080 lb., or just over 2 tons 14 cwt., and the whole battery weighs about 300 tons.

With such a weight to be supported the foundations, insulators, and carriers have had to be carefully designed. As seen in Fig. 1,324, each cell rests upon twelve glass insulators supported by six longitudinal beams, which are in their turn borne by short transverse beams, each resting upon four strong glazed earthenware insulators. The latter rest upon special bricks and concrete foundations, and the floor is finished with acid-proof asphalte.

The connectors from one row to another can also be seen in Fig. 1,324. Each connector consists of four copper bars, each 4 in. by $\frac{1}{4}$ in., set on edge with air-spaces between, the cross-sectional area being thus 1 sq. in. of copper. The bars are suspended from the ceiling by iron rods with globe strain insulators (*see* page 1402) interposed.

The battery room, which is in the basement of the sub-station, is ventilated by two motor-driven fans. One of these draws air from the outside and discharges it at a low pressure through wooden trunks on the floor. The other is a high-pressure fan which draws the air from the battery room through

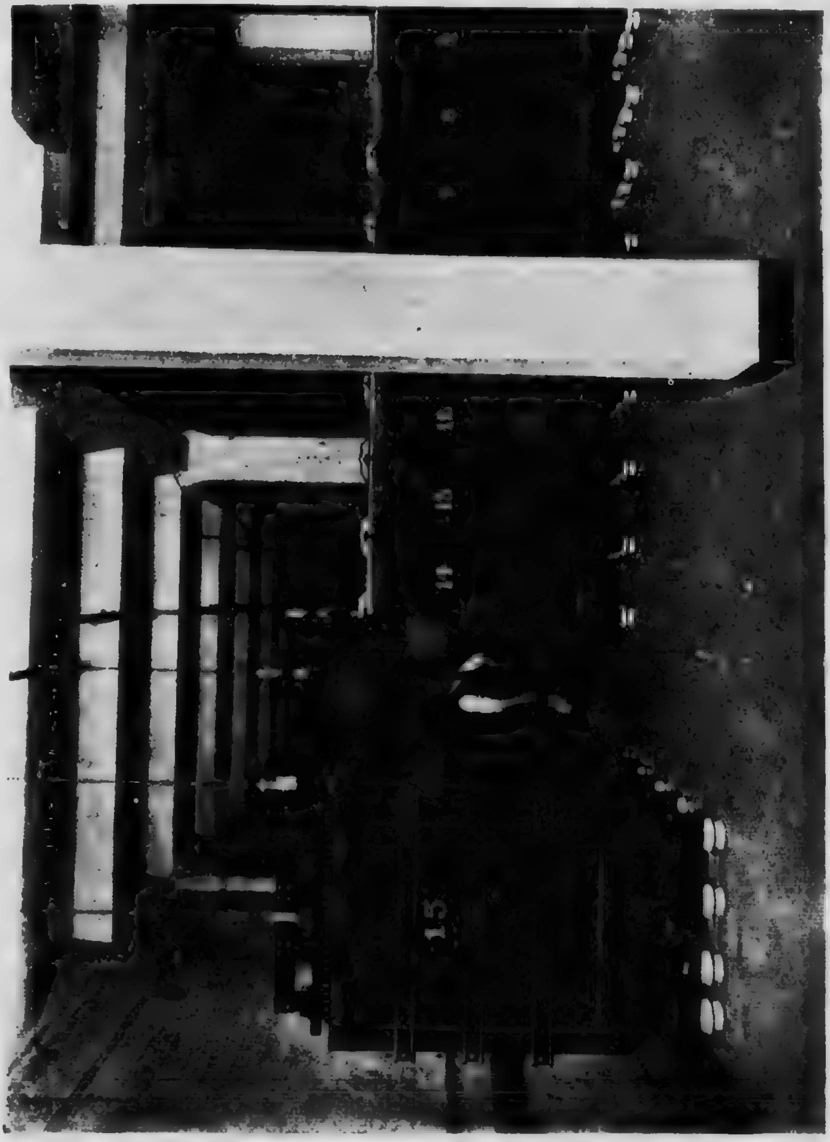

Fig. 1,324. Large Battery in a London Electric Light and Power Sub-station.

a wooden trunk fixed to the ceiling, and discharges it at the top of the building.

The switching and machinery room is over the battery room, and is

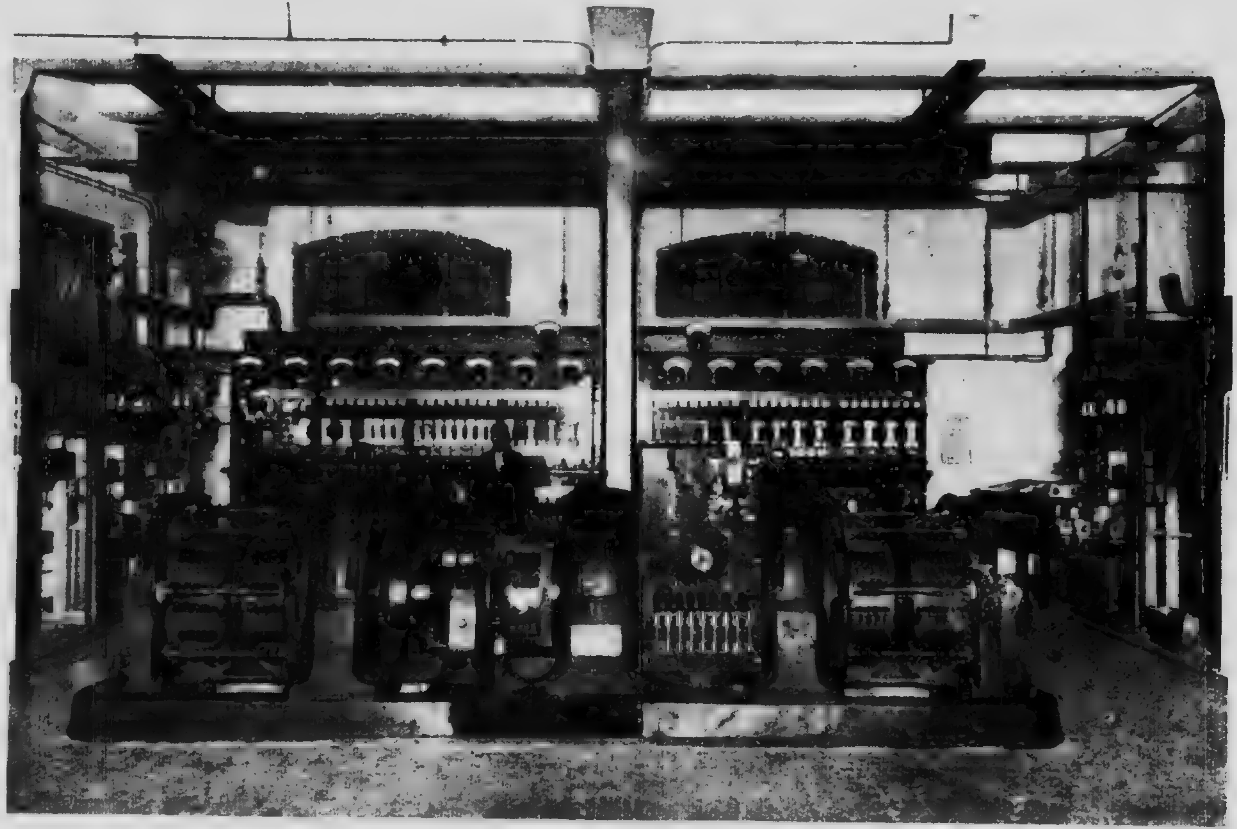

Fig. 1,325. Switchboard with Boosters, Driving motors and Balancers.

Fig. 1,325. Switchboard with Boosters, Driving motors and Balancers.

shown in Fig. 1,325 with the boosters in the foreground and the switchboards in the background and at the sides. There are two E.C.C. booster sets, one behind the other and each consisting of a driving motor in the middle with two boosters on either side. There is no exciter in the set as the boosters are separately excited from the 210–240-volt busbars. Each booster can be made either +ve or —ve, and can give a boost in either direction of 1,800 amperes at 16·7 volts continuously or 3,000 amperes at 10 volts for one hour, its maximum output being therefore 30 *k*w. The efficiency of the boosters varies from 69 per cent. in the former case to 56 per cent. in the latter. The motor of each set gives 115 B.H.P. at 210–240 volts and 500 R.P.M., and has an efficiency of 91 per cent. at full load. Its starting panel and switch gear are seen mounted on the b[illegible].

The feeder, instrument and other panels of the switchboard behind the machine are similar, with minor differences, to those described elsewhere. There are two booster and battery boards on the right and left respectively, one for +ve boosting and the other for —ve boosting. The —ve switchboard is shown in Fig. 1,326. It carries two 5,000-ampere switches for Nos. 1 and 2 boosters respectively, and one 8,000-ampere battery switch, four voltmeters, one recording voltmeter, and one recording ammeter. The recording energy meters are carried on the +ve board.

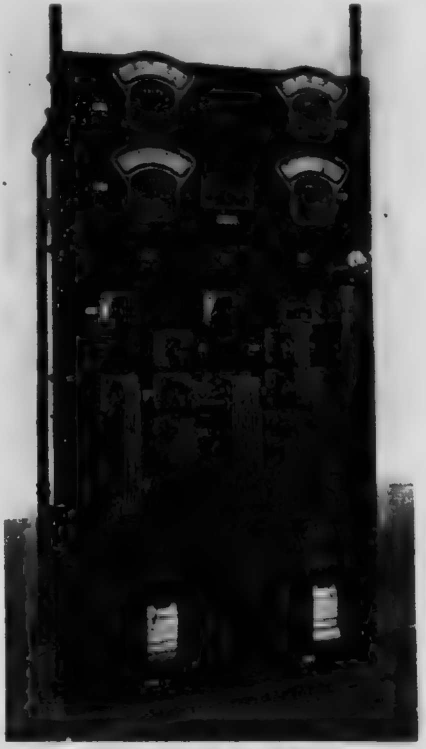

Fig. 1,326.—Negative Booster Switchboard.

III. (i.).—SECONDARY BATTERY REGULATION

The object aimed at in the regulation of a secondary battery in modern systems of electric power generation transmission and utilisation is to ensure that the P.D. at the battery terminals shall remain constant whether the battery is being charged or being discharged and whatever be the magnitude of the current passing through it. As explained on page 1273, the three chief methods employed are (i.) end-cell regulation, (ii.) end-cell and booster regulation, and (iii.) "booster" regulation. examples of each method will now be given.

End-cell Regulation.—This method of regulation was once very extensively used, even on large batteries but, for reasons to be given presently, it has been largely displaced by the methods referred to under (ii.). It is, however, still quite useful in small private and in self-contained installations, and in special cases.

The method deals with the rise of voltage during charge (*see* Fig. 1,076) by cutting out step by step one or more of the cells at one end of the battery as the average voltage per cell increases and with it the total voltage of the battery. On the other hand, when the battery is discharging, and especially towards the end of the discharge, the fall in voltage of individual cells (*see* Figs. 1,074 and 1,075)

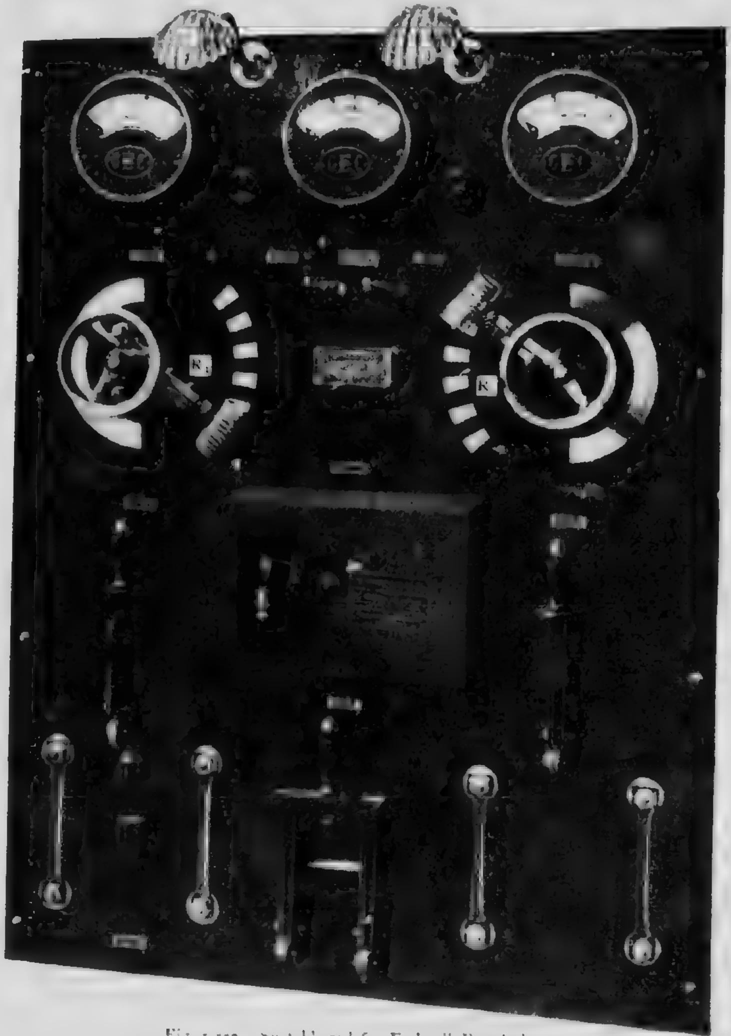

Fig. 1,077.—Switchboard for End-cell Regulation.

is compensated by introducing step by step additional cells at the end of the battery into the load circuit.

The removal and introduction of the cells can be made automatic by means of electro-magnets or of motors controlled by voltage-regulated relays; but such methods are not now largely used, and we do not propose to describe them. Hand regulation is sufficiently convenient for most cases now dealt with in practice by this method.

A standard type of switchboard, as manufactured by the General Electric Company, of London, for plants up to 32 kilowatts output is shown in Fig. 1,327, and a diagram of the connections is given in Fig. 1,328, which shows all the connections for a self-contained domestic lighting plant from the generator to the glow lamps. At the bottom of the board (Fig. 1,327) is the main D.P. switch flanked on either side by a pair of fusible cut-outs and, a little higher up, by two S.P. switches, the one on the left being a throw-over switch with two working positions. The two outermost fuses, one on either side, protect (Fig. 1,328) the dynamo, and the two innermost protect the load, or lamp, circuit, the latter circuit being controlled by the D.P. switch S_0, which is directly in the lamp circuit.

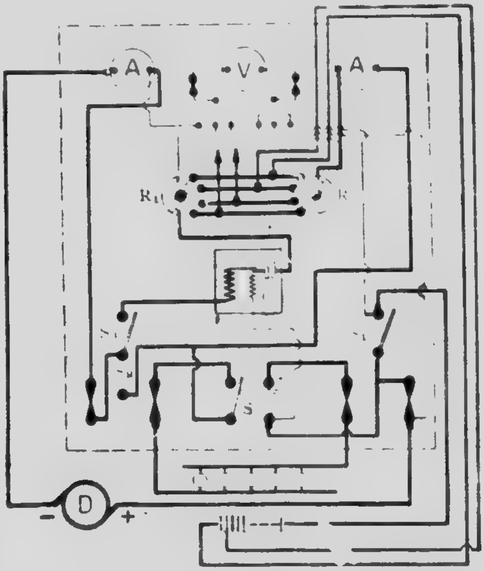

Fig. 1,328.—Connections of End-cell Regulating Board.

Between the two S.P. switches there is on the board (Fig. 1,327) an automatic switch C, and higher up are the two multiple contact regulating switches (R_1 and R_2 in Fig. 1,328), which cut the end cells in and out. The corresponding multiple contacts of these switches are connected by busbars behind the board, the top bar and its contacts being connected to the "—" pole of the last cell of the battery. There are five other pairs of contacts shown in Fig. 1,327, and the voltage between successive contacts may be either 2 or 4 volts, according to the number of cells interposed. Fig. 1,328 shows an interval of two cells, which would correspond to an average P.D. between these auxiliary busbars of 4 volts, thus giving a regulating range for six pairs of contacts of about 20 volts.

Above the regulating switches are the measuring instruments, comprising a voltmeter in the middle, flanked on either side by an ammeter, that on the left showing the dynamo current and that on the right the current flowing to the multiple switch R_2, the continuous arc of which is directly connected to one side of the load through one arm of the D.P. switch S_0. Beneath the voltmeter V is a small three-way D.P. voltmeter switch by which the voltmeter may be made to measure separately (i.) the P.D. of the dynamo, (ii.) the P.D. between the arm of R_1 and the + end of the battery, and (iii.) the P.D. between the arm of R_2 and the + dynamo terminal. When switch S_1 is closed the + terminals of the dynamo and the battery are at the same potential.

A careful study of Fig. 1,328 will show how the following requirements may be satisfied:—

- (*a*) Dynamo charging battery and supplying current to the lamp load at a lower voltage (R_1 and R_2 set generally, as in Fig. 1,328, with switches S_0, S_1 and S_3 closed).
- (*b*) Dynamo and battery, both supplying current to lamp load.
- (*c*) No lamp load, but dynamo charging battery (switch S_0 open).
- (*d*) Dynamo cut out (switches S_2 and S_3 open, S_0 and S_1 closed), and lamp load entirely on battery.
- (*e*) Battery cut out (switch S_1 and S_3 open, S_0 and S_2 closed), and lamp load entirely on dynamo.

When the battery and the lamp load are both in circuit the number of cells on the load depends on the position of the switch R_2. The voltage depends on the state of the cells, and also whether they are being charged or discharged and the current flowing in or out.

The function of the automatic switch C is twofold: first to ensure that the dynamo on starting up shall not be switched into circuit until its P.D. is sufficient to ensure that the current shall flow towards the battery, and secondly to cut out the dynamo if by any chance its P.D. falls below that of the battery, in which case the current through the dynamo would be reversed, and it would be run as a motor by the battery, which, for obvious reasons, must not be allowed.

The switch consists of a balanced arm carrying a copper spanner, which, when the arm is drawn down, bridges the two mercury cups shown in both figures. The movement of the arm is controlled by a polarised electro-magnet, and the arm is so balanced that when there is no current in the coils the spanner is lifted out of the mercury cups and the main dynamo circuit to R_1 is broken. The fine wire coil seen in Fig. 1,328 bridges the dynamo terminals when the switch S_3 is closed, and receives current from the dynamo even when the main circuit is broken at the mercury cups. Whilst the dynamo voltage is being run up, the main circuit being broken, the current in this coil increases until the voltage rises to the value at which it is safe to close the main circuit at the mercury cups, and at this voltage the circuit is closed by the arm of the switch being pulled down. The main current then flows through the thick coil seen in both figures, and the arm is held down. If, however, through the lowering

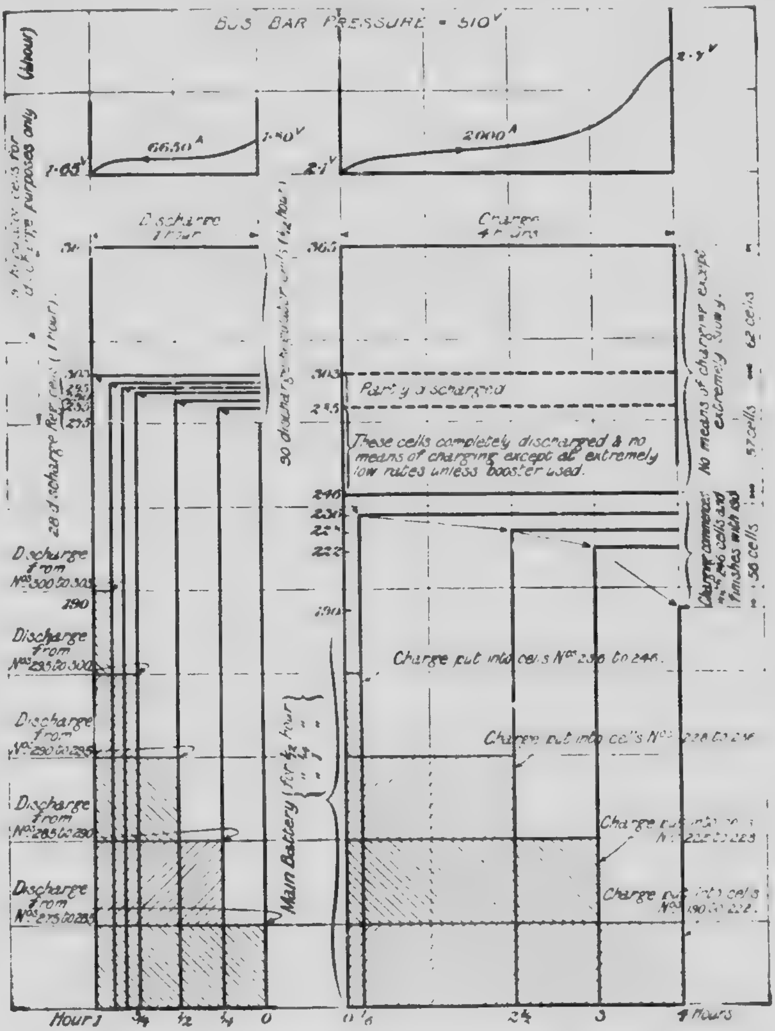

Fig. 1,327.—Particulars of the Inequality of Treatment of End-cells.

of the dynamo voltage, the dynamo current falls nearly to zero, the current in this coil is also diminished, and it can no longer hold down the arm, which flies upwards and withdraws the spanner from the mercury cups, breaking the circuit before the current can be reversed. The circuit cannot again be closed until the fine wire coil again becomes sufficiently energised to attract the arm pulling down the spanner.

There are several objections to the use of the above method of "end cell regulation," especially in the case of the high-voltage batteries employed on traction loads or of batteries dealing with heavy currents and therefore consisting of large individual cells. In the first place, with high-voltage batteries a large number of regulating cells and many multiple contacts on the switches R_1 and R_2 would be necessary. Thus, for a 250-volt battery some seventeen contacts are considered necessary, even when a charging booster is used, as in Fig. 528. Each of these contacts has to be connected to one of the cells of the battery with a lead capable of carrying the full discharge current. Such leads must, where heavy currents are handled, be of large cross section and costly, especially as they may have to be rather long, because it is not possible to place the multiple contact switch in the battery room on account of the acid spray, which would soon corrode the contacts. Further, these end-cells are troublesome to keep in order as compared with the rest of the battery, because their treatment in charge and discharge is abnormal and different from that of the other cells. In consequence, according to the method of working, some may be very much discharged, and then again, others may be overcharged, and amongst their own number the treatment varies.

The inequality of the treatment of the end-cells is shown graphically in Fig. 1,329, which is taken from a paper read by Mr. A. M. Taylor before the Institution of Electrical Engineers.* The diagram, which is for the case of the battery being required in dealing, say, with short peak loads, to discharge at the one-hour rate (see Fig. 1,075), shows how difficult it is to ensure proper treatment of many of the cells. For this case 190 cells are required in the main battery and 113 regulating cells, making 303 in all. The charging is taken over four hours, commencing with 246 cells in circuit and finishing with 190 cells. For the last fifty-seven cells which are wanted for the discharge, there are no means of charging except extremely slowly. The one-hour discharge commences with 275 cells in circuit, but these are increased to 303 for the last few minutes.

The diagram, though not so fully, shows what happens when the battery is required to discharge much more rapidly, namely, at the five-minute (one-twelfth hour) rate (*see* Fig. 1,073). In this case an additional sixty-two cells would be required, which are in the same position as regards being charged as the fifty-seven cells mentioned above. These would have to be fitted with costly regulating contacts and switches, and are virtually a stand-by seldom required.

On the other hand, these extra cells save the installation of additional machinery in the form of motors and boosters, but much of this saving may be lost in the additional number of extra and costly cells which must be installed and maintained. The extra cells necessary for fairly normal working may be forty or more, or an increase of one-sixth in a 500-volt battery as compared with the number required when an automatic reversible booster is used.

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* *Journal of the Institution of Electrical Engineers*, Vol. XLVII., p. 397 (1911).

End-cell and Booster Regulation. A good example of the combination of a booster with end-cell regulation has been given at pages 520-3 in the chapter on Generating Stations. In this example there is a split battery on a three-wire system of distribution, and the regulating cells on each half of the battery are next to the middle or neutral wire with a booster interposed when required. The use of the booster in this way reduces the number of regulating end-cells required. In other systems which are now more frequently used the end regulating cells are entirely abolished, and their place is taken by a booster or boosters, several excellent forms of which are available.

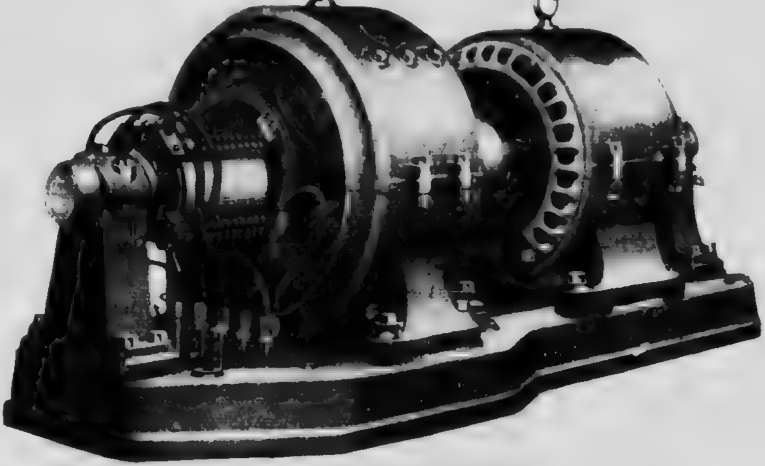

Fig. [illegible].—An Automatic Reversible Booster.

Booster Regulation.—The process of "boosting," as has already been explained at pages 533 *et seq.*, is a process by which the voltage at any point of a circuit may be raised to compensate for a drop of voltage due to any cause arising in the course of operation in a distributing system, such as the drop of voltage in feeders on heavy loads or the drop of voltage due to the discharge of a secondary battery, with which we are concerned more directly here. The "booster," or volt-raiser, employed depends on the conditions, and for the latter case is a C.C. generator, usually motor-driven and controlled, as to its effect on the voltage, either automatically or by hand.

Examples of the employment of boosters in connection with secondary batteries have been given already in the section on "Switchboards an Switching" (*see* pag 518 to 542) in th chapter on Generatin Stations, and it is therefore not necessary t deal further in detai with those method here. The general principle employed has been much elaborated by various designers, and to describe, even briefly, the chief systems which have been worked out would require a great amount of space and would be tedious. It may, however, be interesting to classify the chief systems which have been successfully used somewhat as follows, the classification depending on the type of booster used:

(i.) Self-contained boosters.

(ii.) Boosters requiring a so-called exciter or auxiliary machine.

(iii.) Boosters with an external automatic regulator in their field circuits.

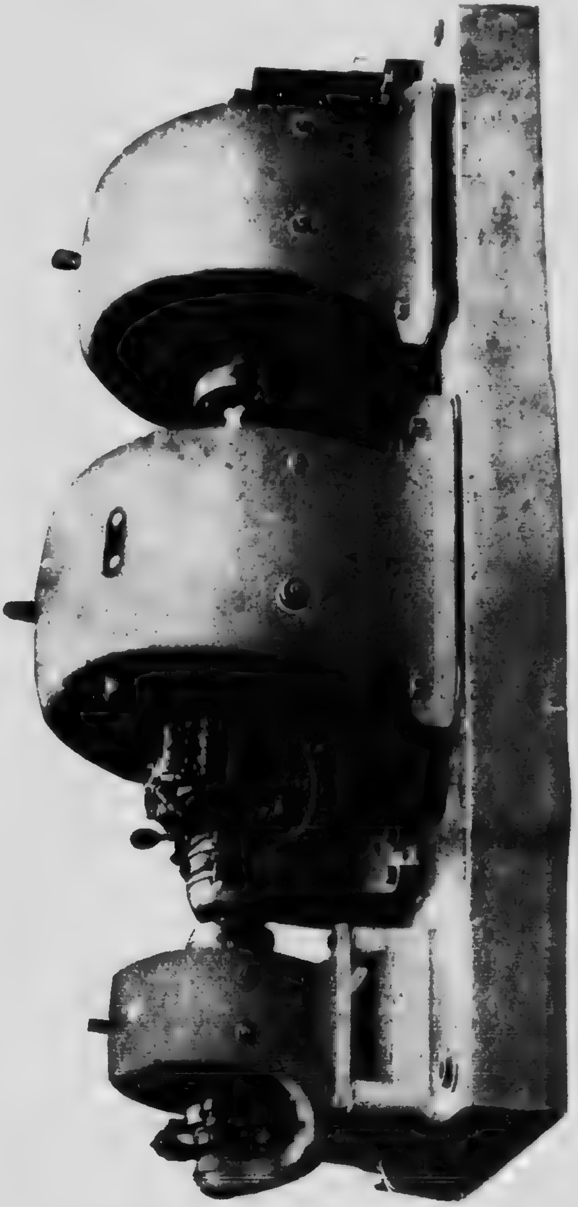

Fig. 1,331. A "Highfield" Automatic Reversible Booster.

The Lancashire automatic reversibl booster, which is an example of type (i.) is shown with its driving motor in Fig. 1,330. It is manufactured by the Lancashire Dynamo and Motor Company, Ltd., and similarly to the booster, whose connections are given in Fig. 538, is wound with four field coils, two series and two shunt wound. Of these one of the series coils is similarly connected to the coil c_2 of Fig. 538 placed between the terminal of the booster and the busbar and carrying, therefore, the booster and battery current, whilst the other is, like c_3, in parallel with diverter resistances placed across a gap in the supply lead from the generator, and therefore carries a current which is a fraction of the generator current. Of the two shunt coils one is a shunt on the booster terminals, as is c_1 of Fig. 538, whilst the other is in effect like c_4, a shunt across the supply mains, but without the reversing switch shown in Fig. 538. The coils c_2 and c_4 are wound differentially, the first to give a voltage in the discharge direction and the second to give a voltage in the charge direction.

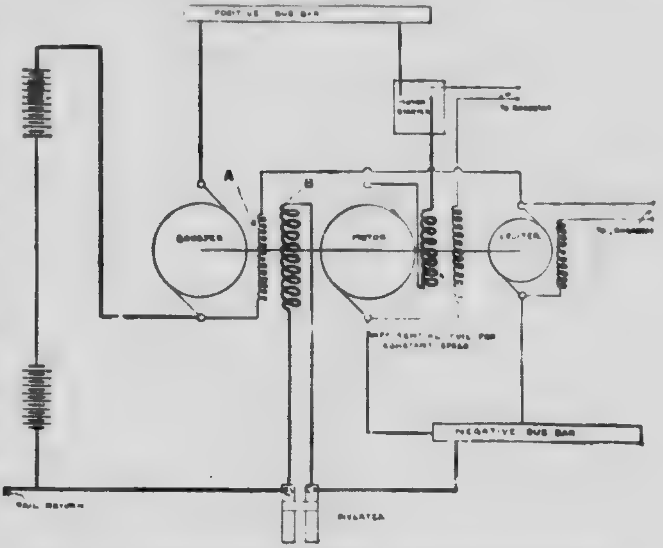

Fig. 542.—Connections of the "Highfield" Automatic Reversible Booster.

The magnetic effect of coils c_1 and c_2 depends upon the direction in which the current is passing through the booster. When the voltage of the battery is equal to that of the generator no current passes through the booster, and the generator takes the load. If the battery is discharging there will be a voltage across the booster terminals assisting the battery voltage, and as the latter voltage falls the P.D. across the booster terminals will rise, and its excitation and consequently its voltage will increase and help the battery. If, however, the battery current changes from discharge to charge, the polarity of the booster will reverse, and its voltage will be in the direction of the charging current. The machine thus acts as a "reversible" booster.

The connections for one example of a booster of the second type (ii.) on page 1288 are given in Fig. 541, when any of the boosters g_3, g_4 or g_5 are being excited from the exciter busbars. In this case the exciters are shown quite separately, and their fields are partly self-excited and partly excited from the busbars, as fully explained in the text. I a self-contained set the exciter, the driving motor, and the generator o booster proper are all on the same shaft, as shown in Fig. 1,331, which is an illustration of the well-known "Highfield" booster. The connectio are shown in Fig. 1,332, which should be compared with Fig. 541. T chief difference will be found to be that in Fig. 1,332 the booster has tw exciting coils instead of one as in Fig. 541. There is the main shunt wound coil A, taking the whole current of the exciter, and the series coil in parallel with the diverter. In Fig. 541 this series coil is on the exciter.

A widely used system of type (iii.) of the classification on page 1288 is the "Entz" booster, the general diagram of which, with the driving motor omitted, is given in Fig. 1,333.* In this system there is only one exciting coil on the booster B, and this coil is supplied with current from the exciter E, which is itself separately excited by a coil C which receives current from the battery, the direction and magnitude of which are controlled by carbon resistances X and Y, which are in series across the whole or a portion of the battery. The coil C is bridged across the junction of X and Y and a point on the battery intermediate between the points supplying current to the resistances X and Y. The resistances consist of piles of carbon discs, whose effective resistance can be varied by the pressure o lever, so arranged that when the pressure on one pile is increased pressure on the other is relieved, and thus, since the actual resist. either pile varies with the pressure, the electric potential of the ju point (*a*) may change through wide limits.

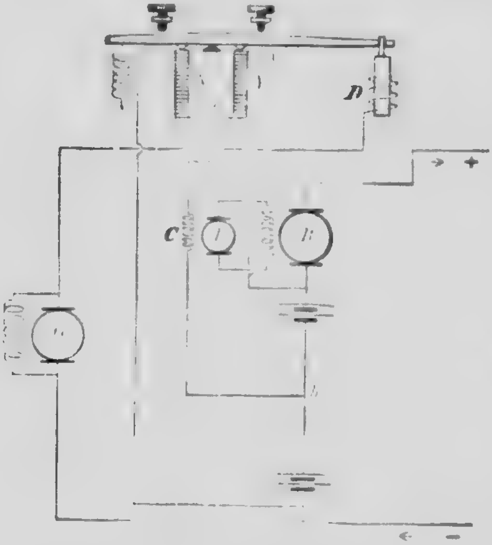

Fig. 1,333.—Diagram of the "Entz" Booster.

The carbon discs and the lever, as mounted on a switch board, shown in Fig. 1,334, kindly lent by the Chloride Electrical Storage Compa To increase the effect, two piles of discs are used on each side of t fulcrum. The position of the lever is controlled by the pull of the of a solenoid D (*see also* Fig. 1,333) acting at one end against the pu spring s at the other end. The tension of [illegible] by the hand-wheel H when [illegible] effect is not being obtained.

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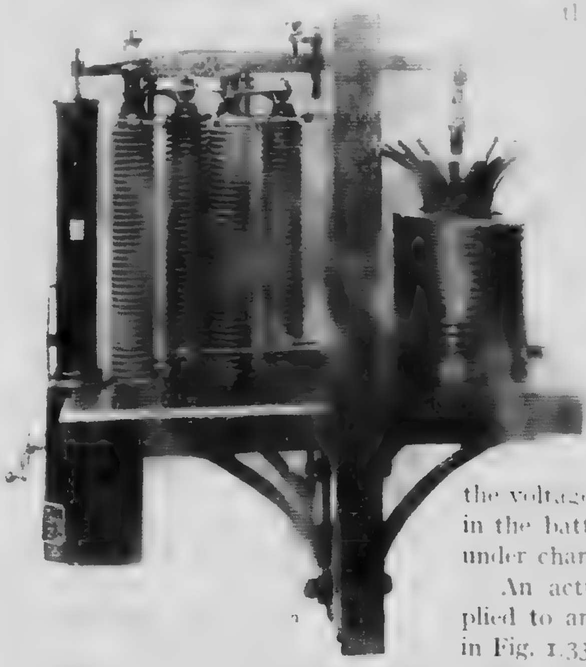
* Taken from a paper by Mr. R. Rankin published in the *Journal of the Institution of Electrical Engineers*, Vol. XLVIII., pp. 283 to 333 (1911).

The coil of the solenoid D [illegible] of [illegible] rator G. When the current [illegible] normal [illegible] the adjustments are such that the potentials of a [illegible] there is no current in C, the exciter is not excited, and the [illegible], the battery simply floating idle on the bus-bars + and −. [illegible] increases the core D is sucked in, cases Y are compressed, and the potential [illegible] rises. The coil C now receives current in the direction [illegible] to [illegible] and the [illegible] ster is excited so that the battery discharges. On [illegible] other hand, if the demand [illegible] and the current [illegible] the spring [illegible] down the left-hand end [illegible] X are compressed and the potential of [illegible] falls so that current flows through C from b to a. This reverses the voltage of B, which being now added, so far as the battery is concerned, to the voltage of G, reverses the current in the battery, which therefore comes under charging conditions.



An actual Entz booster, as supplied to an electric railway, is shown in Fig. 1,335. The motor M is in the [illegible] driven by current drawn direct from the bus-bars. The [illegible] is quite small, being only of 2·5 kw. capacity for [illegible], and it therefore, when required, reverses rapidly. [illegible] also [illegible] is only one exciting coil on the booster, the heat energy [illegible] the [illegible] coils is less than when there are two coils acting [illegible]ially.

[illegible] external regulators have been used in systems coming under [illegible]. Some of these regulators have been already described from [illegible] points of view. Amongst them are the Brown-Boveri regulator (*see* [illegible] 187 to 190), the Thury regulator (*see* pages 104 to 107), the Tirrill regulator (*see* pages 357 to 363), and others. The general principle involved in applying these will be understood from the above description of the Entz booster; lack of space prevents us from dealing with them further in detail.

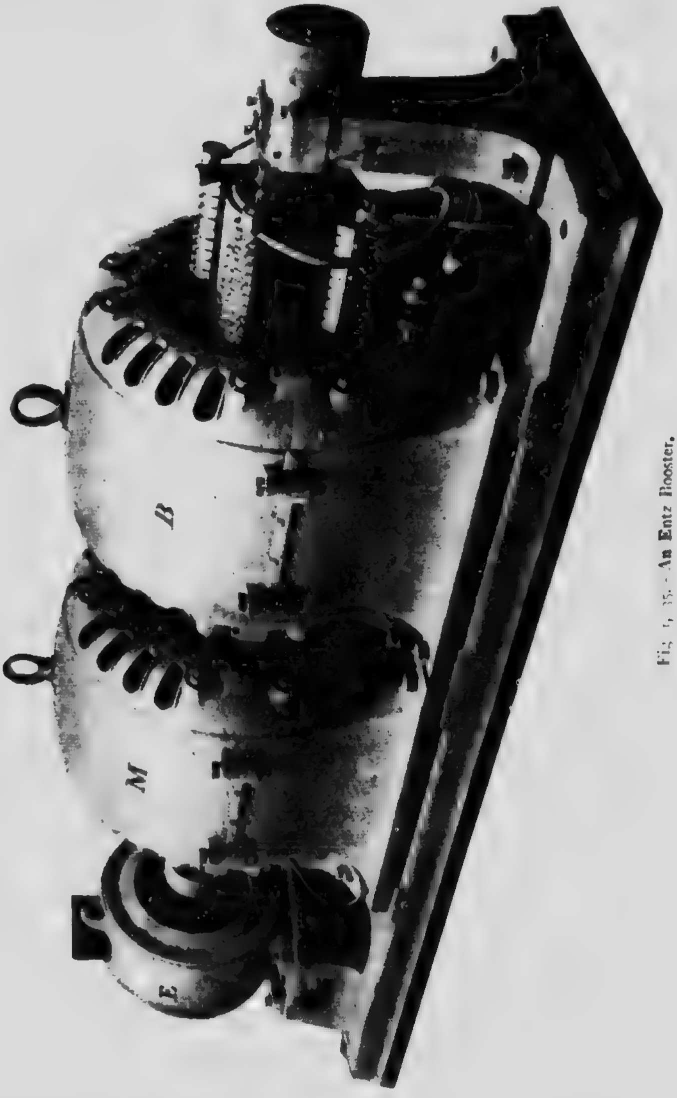


Fig. 1,335.—An Entz Booster.

Effects Produced.—The effect of using a properly regulated battery in a sub-station is exhibited on the records of the instruments shown in Fig. 1,336, which is taken from Mr. Rankin's paper cited above. The ampere load on the sub-station is given by Chart ①, taken by a recording ammeter between the hours of 5 A. M. and 11.40 P. M., during which the load was always fluctuating rapidly, the extreme value being from about 100 amperes to 1,300 amperes. The station was driven by a motor-generator the load on which, as shown by Chart ③, was never subject to rapid variations, but rose and fell according to average

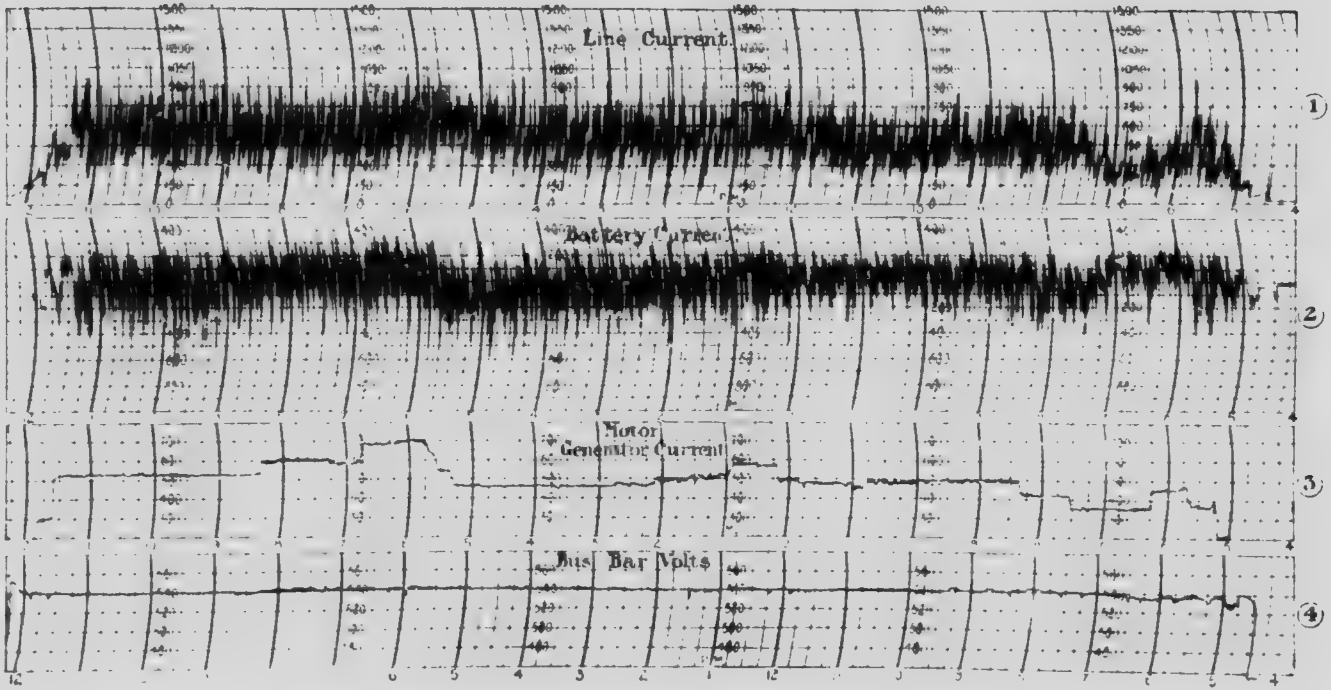


Fig. 1,337. Effect of a Sub-station Battery on Busbar Voltage and Load on Motor Generator.

demands at different periods of the day, the maximum load being 700 amperes (380 *kw.*) and the minimum, during ordinary working hours, about 350 amperes (190 *kw.*). For many hours the load was steady in the neighbourhood of 500 amperes, or 270 *kw.* The most remarkable effect is the almost absolute steadiness of the busbar voltage shown by Chart ④, the deviations from the standard 540 volts being scarcely perceptible and never of long duration.

The explanation is that all the violent fluctuations of load shown on Chart ① were taken up by the battery and the booster, as shown on Chart ②, in which the '+' currents above the zero line are charging currents, and the '—' currents below that line are discharging currents. The former are seldom over 300 amperes, but the latter are quite frequently over 300, and sometimes as much as 600, amperes.

Many charts similar to these could be given, and would be especially valuable in comparing various systems; but the above are sufficient for our purpose, for it is quite impossible to enter upon a minute comparison of the merits and demerits of the various systems alluded to, as well as those which have not been described. The reader, if sufficiently interested, will find a mine of information in the Institution paper cited and the discussion thereon.

IV.—FURTHER OPERATIONS IN SUB-STATIONS

The foregoing sections of this chapter have, either directly or by reference to other parts of the book, dealt with most of the important operations in sub-stations of various types, but there remain a few matters to which attention should be briefly directed, either by way of amplification or addition.

Voltage Regulation.—Directly or indirectly, the regulation of the voltage on the distribution network is one of the chief operations of a sub-station. How this can be maintained constant on the busbars or at the outgoing terminals of the sub-stations has been explained in connection with each of the special types of transformers—static, kinetic, and chemical (secondary battery), already referred to. Incidentally, the throwing in of additional plant in parallel as the load increases bears on the same question, because an overloaded unit may lead to lowered voltage on the distribution busbars.

Use of Feeders.—There remains, however, the necessity of maintaining the voltage at the standard value on the supply-network at distant parts of the network during the heaviest loads. This necessity has led to the development, as part of the system, of *feeders,* to which reference has already been made more than once. But in certain cases it may and does happen that the "drop of volts" on the feeders becomes excessive, and some method of maintaining full voltage at the distant ends must be devised. The two simplest methods, widely used, are :

(i.) The provision of multiple busbars at different and variable P.D.s at the sub-station.

(ii.) The use of "boosters" on particular feeders.

Multiple Busbars.—By providing different sets of busbars and grouping the feeders either permanently or interchangeably on busbars whose P.D.s are different and under independent control, it is obvious that temporary and localised heavy loads can be conveniently handled and full pressure maintained at the consumer's terminals. Examples have been given of this method in the section (pages 518 to 574) describing "switchboards and switching" in generating stations, more particularly in Fig. 528, page 522 ; Figs. 540 and 541, pages 539 and 540 ; and Fig. 555, page 558. Similar devices, *mutatis mutandis*, can obviously be used in sub-stations. In fact, Fig. 540 may be regarded as a sub-station board if the leads from the generators in the diagram, Fig. 541, are replaced by leads from the delivery side of transforming plant receiving energy from high-voltage transmission mains. We refer our readers to these figures as good examples of the use of multiple busbars, seven of which are shown in Fig. 541.

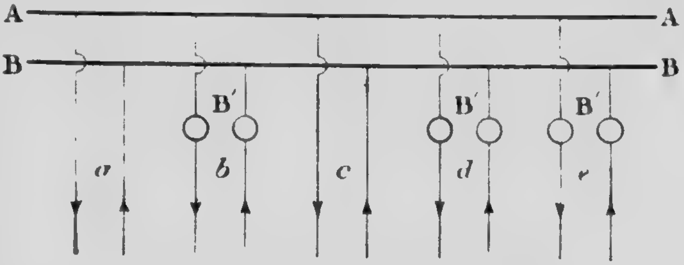


Fig. 1,337.—Diagram of the Use of Boosters on Feeders.

Boosters.—In two of the above examples boosters are used for the purpose of maintaining the required P.D.s on the busbars, but in this application they are ancillary to the generating or transforming plant rather than parts of the distribution system. In the latter they appear on the feeder side of the busbars, and in this position, since they can be allocated to individual feeders, they reduce the number of multiple busbars, which otherwise might be necessary. This use of boosters is shown diagrammatically in Fig. 1,337, as applied to the distribution scheme depicted in Fig. 1,257. The distribution busbars A B (Fig. 1,257) are required to supply current to five feeders of different lengths, two of these, *a* and *c*, being shorter than the other three, *b* *d* and *e*. In Fig. 1,337 boosters B′ B′ B′ are represented as being placed on the longer feeders only. The boosters which should be used are, of course, different in C.C. and in A.C. working.

C.C. Boosters.—These are preferably series-wound dynamos driven by C.C. motors supplied with energy from the distribution busbars. In this respect they differ from the boosters indicated in Fig. 541, which were separately excited machines, the excitation being supplied from the main busbars or from special exciters. The advantage of the series-wound machine when placed on the feeder is that its excitation automatically varies with the current in the feeder, and therefore, as is desirable at heavy loads the voltage "boost" is greater than at light loads, the speed of the machine being maintained constant by the driving motor.

The dynamos employed must be designed as low-voltage heavy-current machines, for the actual boosting voltage required in practice is small compared with the supply voltage. On the other hand the whole current of the feeder must pass through the armature of the booster, the E.M.F. of the armature being in the direction of current flow generator E.M.F.), and the commutator and brushes must be designed to handle this current, which will be a heavy current in comparison with the kilowatt capacity of the machine.

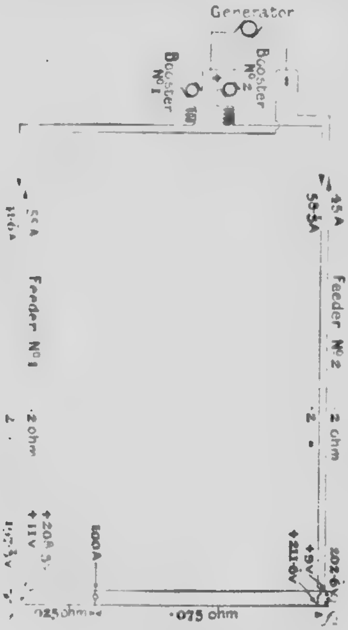


Fig. 1,338.—Feeder Booster on One Wire Only.

A number of interesting problems, which we cannot consider in full detail, arise out of the use of series-wound boosters on feeders. For instance, in Fig. 1,337 we show boosters on both wires of each feeder. This is necessary because it can be shown that the currents in the two feeder wires would with one booster only not necessarily be equal. A case of this kind, worked out by Mr. W. A. Ker,* is given in Fig. 1,338, in which two feeders are required to supply current for a load of 100 amperes unsymmetrically placed as regards the feeding points f_1 f_2. Full details of resistances, currents and potentials are given in the diagram and should be carefully studied. It will be noticed that the P.D.s at f_1 and f_2 are not the same. Moreover, No. 2, the feeder further from the load, is more heavily loaded than No. 1, which is nearer. The result of introducing a booster into each wire of each feeder is shown in Fig. 1,339, in which the P.D.s at the feeding points are each 200 volts, and No. 1 feeder, which is nearer the heavy load, bears the proportionately heavier current. With these interesting examples we must leave the subject.

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* *Journal of the Institution of Electrical Engineers*, Vol. XLIV., page 487 (1909).

A.C. Boosters or Regulators.—These will usually take the form of static transformers, which at first sight make the operation of feeder boosting appear to be much simpler than in the continuous-current case. There are, however, restrictions. If an ordinary static transformer, with fixed high- and low-pressure coils be used, the high-pressure coil will be bridged across the full voltage of the bus-bars, and the low-pressure coil will be in series with one wire of the feeder. This will definitely raise the voltage on the feeder by a fixed amount, largely independent of the load, except that with heavy load currents the "drop" in the transformer will be increased. There will be a permanent "boost" for all loads, but for heavy loads the amount of boost will diminish, which is not what is wanted.

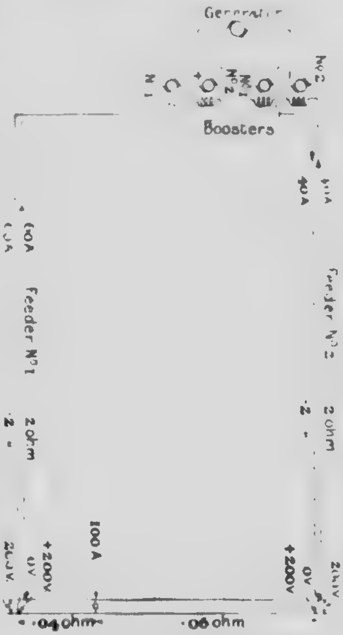


Fig. 1,339.—Feeder Boosters on Both Wires.

One obvious way which will partially meet the difficulty is to have various *tappings* on the low-pressure coil and, either by hand or automatically, to switch more windings into circuit as the load comes on. This, however, only gives a limited number of fixed boosting pressures, and lacks flexibility. One example of this method has already been given at page 545 (Figs. 544 to 546), in describing the A.C. low-voltage feeder board at the Northampton Polytechnic Institute. Three single-phase booster transformers, with suitable tappings, are placed upon the incoming leads from the step-down transformers, and by means of a special switch the pressure on the outgoing three-phase feeders can be varied from 310 to 390 volts by eight steps of 10 volts each.

Another example of a hand-operated regulator, as made by the British Thomson-Houston Company, is illustrated in Fig. 1,340. An oil-immersed self-cooled, 22-*k*w. transformer is suspended in the tank, upon the top of which is mounted the dial switch, which can either be operated by the handle shown or, if fitted with a sprocket wheel or bevel gear, can be operated from the switchboard. The secondary of the transformer is divided into ten sections, tappings being brought to the successive points of the switch, and through the switch one or more of the sections connected in series with one of the leads of the feeder. Starting with the switch in the position in which all the coils are raising the voltage on the feeder, that is, in the position of maximum boost, the first revolution of the dial diminishes the boosting voltage step by step by cutting out in successio the several sections of the low-pressure winding. When the first revolution has been completed the voltage of the feeder is the same as that o the busbars, the low-pressure windings being entirely cut out of circui Turning the switch still in the same direction, the next movement throw over a reversing switch on the back of the slab, and on continuing th motion the low-pressure windings are cut in again step by step, but wit their polarity reversed. This throws an increasing negative pressure i series with the feeder, until in the final position of the switch the feede voltage is "depressed" by an amount approximately equal to the previou maximum boost. If now the voltages have been so arranged that thi lowest pressure corresponds to the no-load voltag required, the apparatus gives a rising variation o pressure in twenty successive stages.

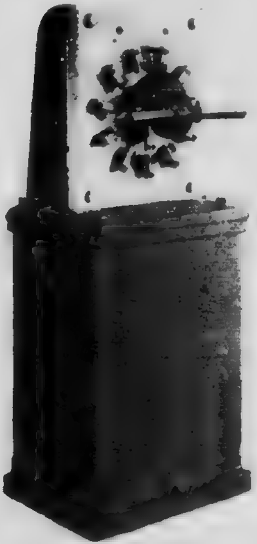


Fig. 1,340.—Hand-operated A.C. Booster and Depressor

By means of a motor and a clutch, and with a modification in the form of the contacts, th switch can be arranged to work automatically, th motor and clutch being controlled by a suitabl electro-magnetic device which we have not spac to describe. The accompanying Fig. 1,341 gives the internal connections, the barrel carrying the collector rings and fingers being the part operated by the motor and clutches. It will be noticed that one end of the cut feeder is brought to the middle of the secondary windings, which in this case are divided into twenty sections. The coils on the right of the junction act as booster coils, and those on the left as depressor coils. The other end of the cut feeder is brought to the preventive resistances, which are in series with the contact fingers, each through a collector ring By this device the changes in the voltage are made gradual instead of being in sudden steps

In the above regulators it will be understood that the current passing through the primary or high-pressure coil is lost to the feeder, and this current will not be a negligible quantity. The theoretical distribution of currents and voltages, assuming 100 per cent. efficiency in the transformer, is shown in Fig. 1,342, in which it will be seen that the 10 per cent. rise in voltage leads to a 9·09 per cent. loss of current.

On the other hand, and with the same assumption, Fig. 1,343 shows how the loss of voltage when the transformer is acting as a depressor is compensated by a corresponding increase of current.

Induction Regulators. These, for single-phase working, are also static transformers in the sense that when they are set for a given voltage effect the primary and secondary windings are stationary with respect to one another. To allow of a variation of the voltage effect, however, one of the windings can be moved relatively to the other. For polyphase working they resemble the stator and rotor of an induction motor more than an ordinary transformer. We take the two cases separately.

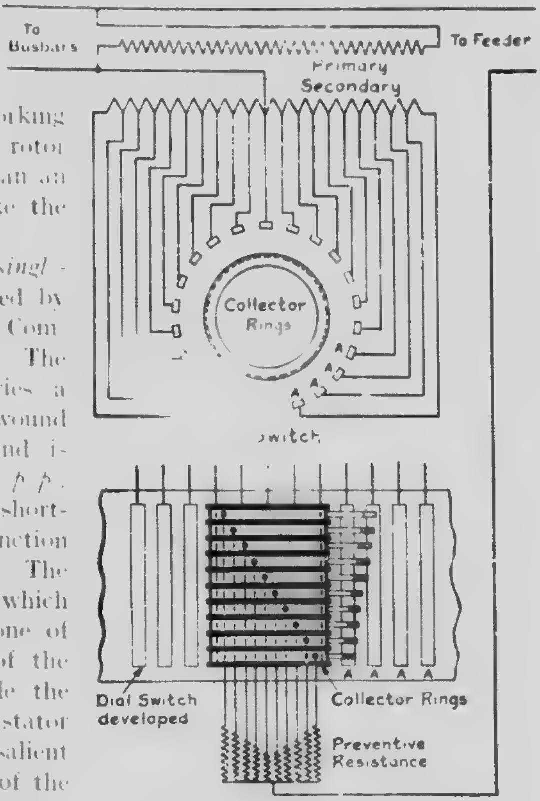


Fig. 1,34[illegible]. Connections of an A.C. Booster and Depressor

The various parts of a *single-phase* regulator as manufactured by the British Thomson-Houston Company are shown in Fig. 1,344. The primary winding, as it carries a constant and small current, is wound upon the movable core P and is contained in the vertical coils *p p*; the horizontal coils *c* are short-circuited windings whose function will be explained presently. The secondary or series windings, which are to carry the current of one of the feeders, are in the slots of the laminated core built up inside the casing S S like the core of the stator of an induction motor with salient poles. The relative positions of the two circuits are shown diagrammatically in Fig. 1,345. As the currents in each winding are single-phase alternating, the magnetic fluxes will be at right angles to each winding (i.e. in the positions shown in Fig. 1,345 they will be horizontal. In this position of the primary windings the two fluxes are also in the same direction, and as this direction is such as to produce a back E.M.F. in the secondary windings the net result is that the voltage induced in the secondary by the primary flux is a depressor

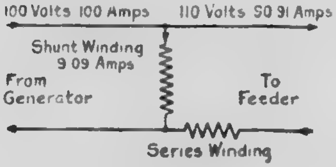


Fig. 1,346. Connections of an A.C. Booster.

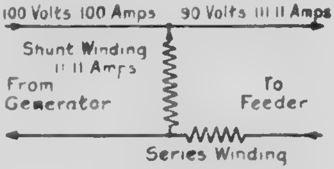


Fig. 1,347. Connections of an A.C. Depressor.

voltage and is to be subtracted from the line voltage. If, however, the movable primary be rotated 180° the two fluxes will be in directly opposite directions, and the induced voltage in the secondary will be added to or boost up the line voltage. When the parts shown in Fig. 1,344 are assembled and ready for working the completed regulator is as shown in Fig. 1,346, the axes of the concentric parts being vertical. The motor M (Fig. 1,344) is mounted on the top of the casing and is geared through the wheel and pinion and endless screw to the gear wheel W, which is keyed on to the top of the shaft of the movable core. By proper electro-magnetic control of the motor this core can be automatically rotated through the full range of 180° from maximum lowering to maximum boosting of the line voltage. As the core is thus gradually rotated, the relative direction of the primary flux and consequently the proportion forced through the secondary windings, is similarly varied, and produces a gradually varying value from the maximum — value through zero to the maximum + value. The induced voltage is, however, always in phase with the primary current and is therefore added directly to or subtracted directly from the line voltage.

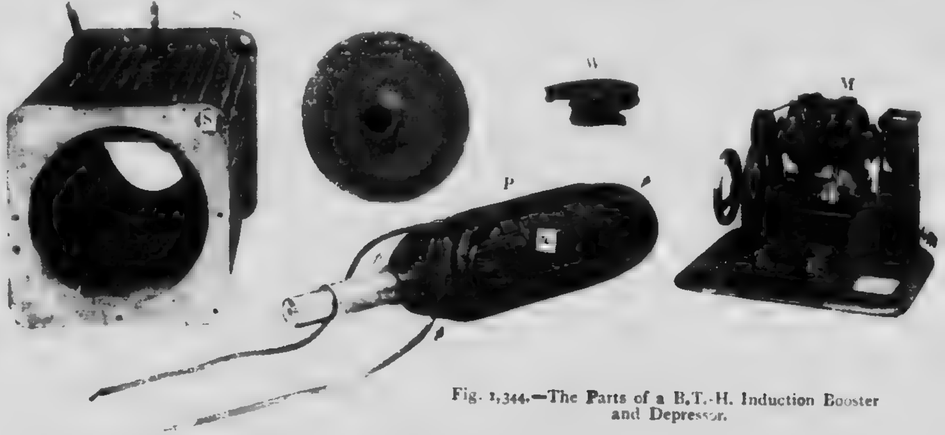


Fig. 1,344.—The Parts of a B.T.-H. Induction Booster and Depressor.

The function of the short-circuited winding on the movable core is to decrease the inductive reactance of the regulator. In the extreme positions it has no effect; the magnetic fluxes do not pass through its coils, in which, therefore, there is no induced E.M.F. and no current. In every other position of the core the flux from the secondary coils partially or, in the zero effect position, wholly passes through these windings and induces a current in them which sets up an opposing flux diminishing the inductive reactance in the secondary circuit and, if properly designed, leaving the voltage drop in the zero position affected only by the ohmic resistance. Incidentally, this also means that in this position, in which

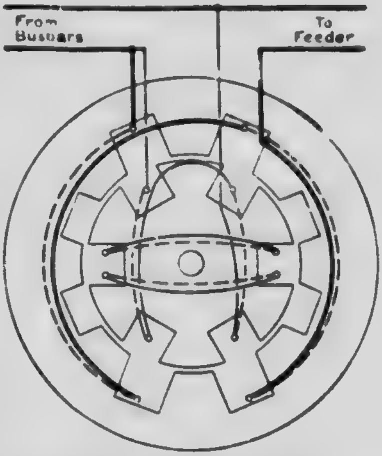


Fig. 1,345.—Connections of a B.T.-H. A.C. Single-phase Regulator

without this short-circuited winding the regulator would act as a choking coil on the feeder, there is practically no effect on the power-factor of the feeder. Put otherwise, it ensures, as shown by actual tests, that the sum of the ampere-turns of the two windings on the movable core are always approximately equal in every position of the core to the ampere-turns of the secondary at full load.

Polyphase Induction Regulator.—In this case the fixed and movable cores shown in Fig. 1,344 are wound like the stator and wound rotor of an induction motor, except that they are wound in wide slots with salient poles. Care must be taken that each pole, whether of stator or rotor, is wound with as many distinct and separate windings as there are phases, and that these windings are connected to the line in the proper phase order. This is to ensure that the magnetic field in each case is a uniform rotating field, the speed of rotation being fixed by the periodicity and the number of poles and being in the same direction for both cores.

Fig. 1,346.—A B.T.-H. Automatic or Hand-operated A.C. Single-phase Regulator.

As in the preceding case, the regulation is effected by altering the angular position of the rotor from the position in which the two rotating fields are in directly opposite phase, which is the position of maximum boosting, to that in which the phases coincide, which is the position of maximum depression of the line voltage. In any intermediate position the booster or the depressor effect depends upon the phase difference between the two fields set up by the angular position of the rotor.

A 150-*k.w.* three-phase air-cooled regulator, manufactured by the British Thomson-Houston Company, is shown in Fig. 1,347. The connections to the shunt and series circuits are made by means of the twelve flexibles which are seen hanging over the sides. The rotor can be operated by the hand-wheel or automatically by the electro-magnetically controlled motor on the top of the cover. The regulator in Fig. 1,347 is designed t run on a 4,000-volt feeder at 50 ∿, and therefore, as is the regulator shown in Fig. 1,346, is not intended for low-voltage distribution. There are, however, a number of cases in which an intermediate step-down station at such voltages requires regulators for feeders supplying energy to a number of consumers' low-voltage sub-stations. In designing such A.C. low-voltage regulators the same principles apply.

The efficiency of these polyphase regulators is 92·5 to 96·5 per cent. of the capacity of the regulator, which is small compared with the capacity of the line. The single-phase regulators previously described have an efficiency of 93·5 to 96·5 per cent., according to size.

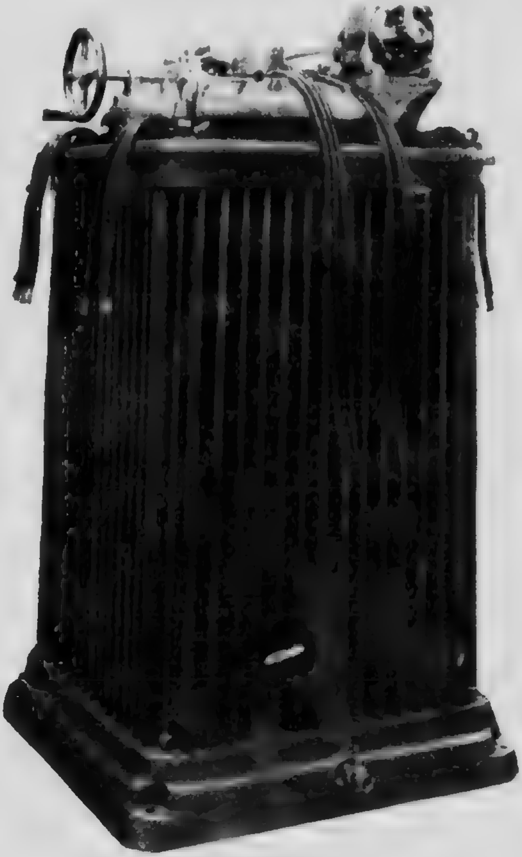


Fig. 1,347.—A B.T.-H. Three-phase Regulator.

Balancing on Three-wire Systems.—In three-wire systems of distribution, in addition to keeping the P.D. constant at the ends of long feeders, there arises the further problem of dividing the voltage equally between the outers and the neutral wire when the loads on the two sides are out of balance. The problem is of practical importance, especially in C.C. schemes, which, in this connection, are very much more numerous than A.C. ones.

The importance of finding a solution will be apparent from considering the simple case depicted in Fig. 1,256, and by supposing that the poles of a 500-volt dynamo are connected to A and C whilst B is left unconnected. The "factory" being connected across the "outers" presents no difficulty; it gets its supply at 500 volts, whatever the other consumers may be taking. But houses 2, 3, 4, and 6 are on the "+" side of the system, and houses 1 and 5 on the "—" side. Assume now that the load in these houses consists entirely of similar glow lamps, and that at a certain time houses 1 and 5 have forty lamps switched on, whilst houses 2, 3, 4, and 6 have only thirty burning. The forty lamps can only get the current which has passed through the thirty lamps, which will mean that the thirty lamps will receive too much current and the forty too little. In fact the P.D.s between neutral and outers will so adjust themselves that the voltage will rise considerably above 250 on the + side, and to the same extent fall below 250 on the − side. The lights in 2, 3, 4, and 6 will be abnormally bright, and those in 1 and 5 abnormally dull. Half an hour later the conditions may be reversed, and the lights on the + side be dim, whilst those on the − side will be too bright. Evidently such fluctuations would not be tolerated by ordinary consumers, and therefore some automatically acting apparatus should be brought into action which will maintain the P.D.s between A and B and between B and C at 250 volts whatever the demands of the different consumers may be. Here again the apparatus and arrangements differ for C.C. and A.C. system

C.C. Balancers. The elementary principles of the oldest and probably the simplest solution of the problems involved have been explained and illustrated in the historical section, in which a real motor-generator, that is, a single machine, is used as the convenient kinetic transformer (*see* Vol. I., pages 631 to 635). The armature has two identical windings with two commutators, and these two windings are put in series across the outers, the common junction being attached to the neutral conductor of the distribution system. A coupled plant set in use for C.C. balancing on a three-wire system is also illustrated in Fig. 607, Vol. I., and a good modern balancer set is shown in the foreground of Fig. 472, Vol. II., installed in a modern generating station.

A good practical example of the method has been given at page 537 of this volume where there is described, with a diagram (Fig. 539) of the connections, the C.C. balancer panel of the Northampton Polytechnic Institute. The various devices for securing the objects aimed at are carefully worked out and might well be re-read in the present connection. Another example, not so fully worked out, is given at page 520 (Figs. 527 and 528).

From a study of the above it will be realised that when the two sides of the three-wire system are in balance, both armatures, where there is not a separate driving motor, take a motor current just sufficient to supply the energy wasted on frictional losses mechanical, electrical, and magnetic. It is thus necessary that a back E.M.F., nearly equal to the voltage between the neutral and the outer, should be developed in each armature. As in this case the series current is inappreciable, the main excitation is supplied by shunt windings which can be supplied in one of the three ways (*a*), (*b*), or (*c*) shown in Fig. 1,348.

When the system is out of balance, as shown in Fig. 1,348, by the unbalanced current C_3, the voltage on that side would become lowered if there were no balancer, and the voltage on the other side raised. The current in the armature A_1, helped by its E.M.F., is reversed and becomes a generator current, whilst that in A_2 is unchanged in direction, but is increased, and, being against the E.M.F., remains a motor current supplying the extra energy to enable A_1 to act as a generator. Under these circumstances it is obviously desirable not to diminish the excitation of A_1, and therefore the arrangement (*c*), which supplies the excitation from the opposite side where the voltage is raised, is a better arrangement than (*b*), in which the excitation of A_1 would remain unchanged, or (*a*), in which it would be actually lowered. This, it will be found, is the arrangement adopted for the shunt excitation in Fig. 539.

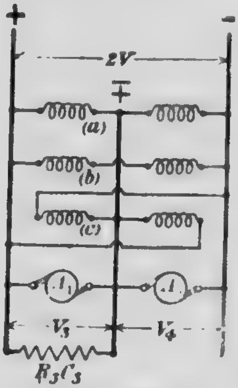


Fig. 1,348.—Methods of Excitation of Three-wire Balancers

To assist the excitation series windings are also employed and are so connected up as to weaken the flux when the machine is motoring, and strengthen it when the machine is generating. In Fig. 539 these windings on the two machines are in series and carry the out-of-balance current of the neutral wire. This current will be reversed whenever the larger load changes over from one side of the system to the other, and thus the required kind of influence on the two fluxes can be obtained automatically under all conditions of want of balance by thus connecting the windings in series.

Another method of connection is shown in Fig. 1,349, in which the series windings S_1 and S_2 are crossed, as well as the shunt windings sh_1 and sh_2. In this case each series winding carries the whole current of the armature on the opposite side of the system. There is little to choose between the two methods of connecting up, but in the case of a heavy overload on one side, the method of Fig. 1,349 is rather better than that of Fig. 539.

Finally, with regard to the excitation of balancers, two devices appear in Fig. 1,349, one of which is not in the other figures. In this figure there are interpole windings $I\,P_1$ and $I\,P_2$, each in series with its own armature, since the effect of interpoles on the commutation (*see* pages 107 *et seq.*) depends upon the current in the armature under commutation, and must be reversed with that current. The other device is the regulator resistance R, which is inserted in the junction between the two shunt windings, and which is electrically the same as the rheostat H_1 in Fig. 539. This adjustable rheostat is not absolutely necessary, but can be used as a convenient fine adjustment in special cases.

The middle-wire ammeter A_3 in Fig. 539 and C_3 in Fig. 1,349 is necessarily a centre zero instrument, giving information not only of the magnitude, but also of the direction of the out-of-balance current. The voltmeters V_3 and V_4 (Fig. 1,349), and B (Fig. 539) are also a very necessary part of the balancer equipment.

Should the reader desire to pursue the subject of C.C. balancers further, together with the details of the calculations connected with them, he cannot do better than consult a series of seven articles by Mr. Thomas Catter[illegible] which appeared in *The Electrician* in January and February, 1917, and from which Figs. 1,348 and 1,349 have been taken.

Rotary Converters as Balancers. In a rotary converter st[illegible] the regular equipment supplies a ready-made method of balanc[illegible] wire system provided the C.C. side of the rotary is at the pro[illegible] for connection to the "outers." If the reader will refer to [illegible] and 1,021 he will find the method indicated by a dotted line in each figure running to the neutral wire from a mid-coil tapping of the windings of one of the low-pressure coils of the three-phase high-voltage transformer. It is a matter of indifference which of the three coils be chosen, for, as we have already shown, the mid-points of the coils are all at the same potential and might be permanently joined together.

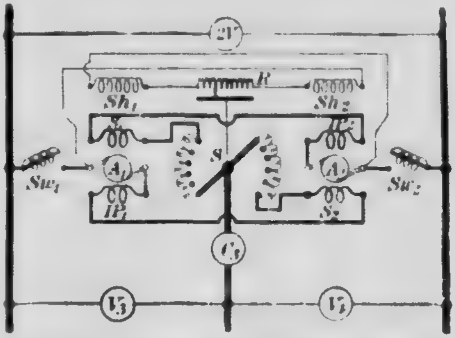


Fig. [illegible] Three-wire Ba[illegible]

This may be again made clear by a careful study of Fig. 1,014, in which the lower part is a diagrammatic sketch for a bipolar rotary of the commutator, armature windings, slip rings, and secondary coils of the transformer in their correct electrical positions, the star-connected primary coils being indicated in the upper part of the figure. At page 987 it is shown that the mid-points of the secondaries are all at the same potential, and that this potential is midway between the potentials of the two brushes on the commutator, and is therefore the balance potential of the neutral of the three-wire system when the brushes are connected to the outers. Wires could therefore be brought from these mid-points, as indicated by dotted lines, and connected to a short-circuiting switch S, whose common terminal is joined to the neutral wire.

If the distribution system be out of balance so as to raise, let us suppose, the potential of the neutral wire, a continuous current will flow from the neutral wire through the secondaries of the transformer and slip rings to the armature, where it will be distributed amongst the windings in such a way that certain parts of it will flow against the inductive E.M.F.s and act as motoring currents, and other parts in the direction of the E.M.F.s and act as generator currents. The distribution, in accordance with Lenz' general law (*see* Vol. I., page 418), will be automatically such as to tend to cancel the cause which gives rise to it—namely, the raised potential of the neutral wire, which will be accordingly reduced in the direction of restoring the balance.

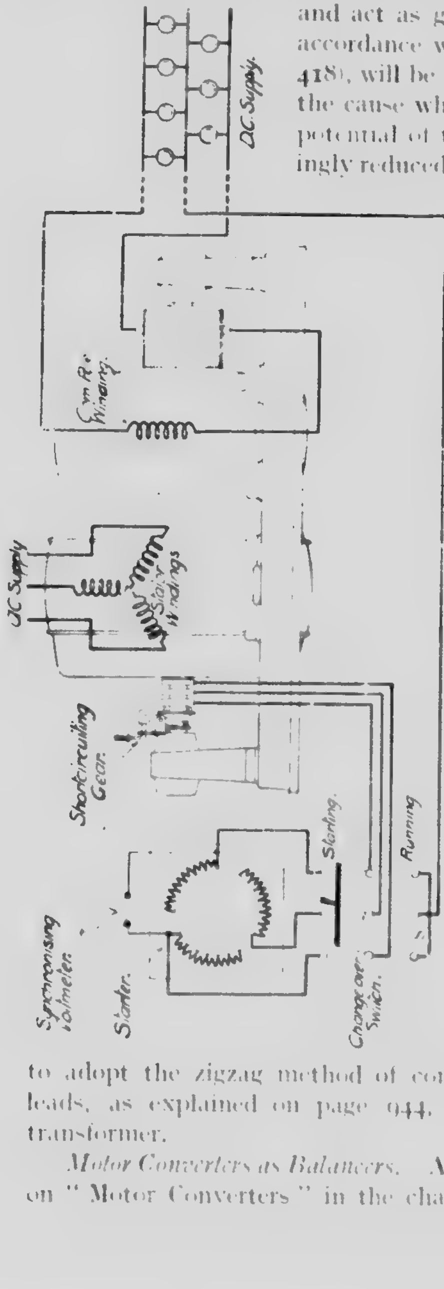


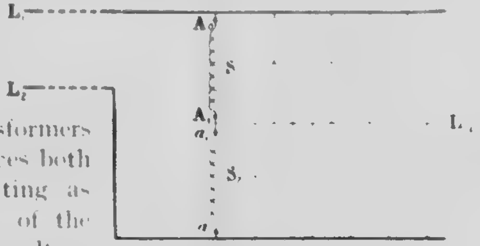
FIG. [illegible]. Connections for a Motor Converter as a Balancer

The solution is simple and effective, and calls for no further comment except that the passage of these continuous currents through the secondary coils of the transformers does not alter their magnetic flux, since each current reaching the mid-point of a secondary coil divides, in practice, equally, right and left, and produces in the two halves, which, of course, have the same number of turns, magnetic effects which cancel one another and leave the magnetising ampere turns of the coil unchanged.

Should the rotary converter be three-phase instead of six-phase, all that is necessary to apply the same principle is that the transformer secondaries should be star-connected, and that the neutral point of the star should be joined to the neutral wire of the three-wire distribution system. For a proper balancing out in this case of the magnetic effects of the continuous currents in the secondaries of the transformer, it is necessary to adopt the zigzag method of connection shown in Fig. 965, and this leads, as explained on page 944, to an increase in the cost of the transformer.

Motor Converters as Balancers. At the end (*see* page 1016) of the section on "Motor Converters" in the chapter on kinetic transformers, it is remarked that the rotor of the induction motor may be connected to the neutral point of a three-wire system, and that the converter will then act as a balancer.

The point of connection to the neutral wire is shown diagrammatically in Fig. 1,350, and is already provided by the regular method of starting the converter shown in Fig. 1,030 and described on page 1012. All that is necessary is to provide a change-over switch S (Fig. 1,350), which can take the place of the short-circuiting plug P in Fig. 1,030. As the armature of the motor converter is connected up in the same way as the armature of a twelve-phase rotary converter would be, the distribution of the out-of-balance currents in that armature leads to less disturbance from heating effects than in a six-phase machine, and it is found that with an out-of-balance current up to 50 per cent. of the full-load current the variation of the voltage between the two halves of the distribution system does not exceed 1 per cent. of the voltage between the outers.



[illegible]

A.C. Balancers. Static transformers are able to perform valuable services both in A.C. and C.C. working by acting as "static balancers," taking charge of the out-of-balance currents for which the voltage of the main supply circuits is subdivided between loads which may be varied independently of one another. Three important cases in practice are:

(i.) A three-wire single-phase A.C. load connected between doubled voltage mains and a third or neutral wire.
(ii.) Three single-phase loads, connected respectively between the mains and the neutral wire of a three-phase system.
(iii.) A three-wire C.C. load connected between doubled-voltage outers and a third or neutral wire.

Alternate-current Three-wire Balancers. This is a comparatively simple case. Instead of the three wires being all led back to the main distributing transformer at the sub-station, only the two outers are taken back to the secondary terminals of the single-phase transformer. Quite near to the load these two outers L_1 and L_2 (Fig. 1,351) are connected to the coils S_1 and S_2 of a 1-to-1 transformer with its primary and secondary connected in series as shown. The third wire L_n of the distribution system is connected to the common junction.

If now the loads on the two sides are not balanced, but one of them be the greater, then without the balancer the potential difference (V_2) on the side $L_n L_2$ of the greater load would, as in the C.C. case, be less than the potential difference (V_1) on the other side $L_1 L_n$. With the balancer inserted, part of the current for the greater load L_0 L_2 will pass through the coil S_1, which will be carrying a greater current than the coil S_2. This increased current in S_1, acting inductively on S_2, will boost up the voltage V_2, whilst the voltage V_1 will be lowered. Thus the voltage balance is, at least in part, restored. The increased current required on the side L_0 L_2 may roughly be regarded as obtained as to one-half by the increased current in S_1, acting as a primary coil, and as to the other half from the output of S_2, acting as a secondary coil.

The size of the balancing transformer is much less than that of the main transformer, even if the load which it deals with is the whole load. Thus if at full load on one side there is only 75 per cent. load on the other side, the output of the balancing transformer need only be one-sixteenth of full load on the main transformer. The voltage on each coil of the balancing transformer is at no load, that is, with the two external loads perfectly balanced, half of the voltage between the outers. By placing this small transformer close to the load the cost of running back the third wire to the main transformer will be saved.

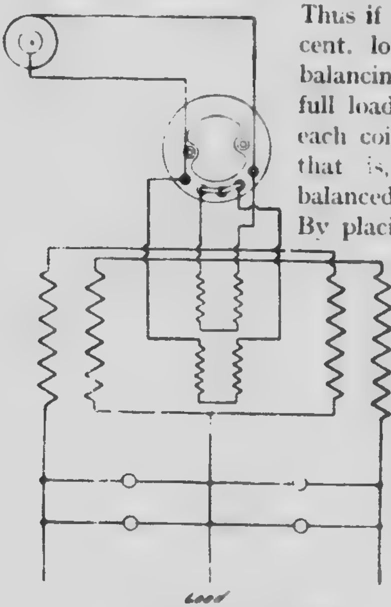


Fig. 1,352. Arrangement of Windings of a Three-wire Transformer.

The balancing on an A.C. three-wire single-phase system may also be effected by the step-down transformer in the sub-station if the distribution network is close at hand, and the neutral wire can be conveniently brought into the station. The neutral wire is, of course, connected to a tapping from the middle of the secondary of the step-down transformer whose terminals are supplying current to the outers. If, however, balanced voltage is to be maintained the secondary windings must be carefully distributed. The method employed by the General Electric Company, of Schenectady, in the core type of transformer described at page 800 (Figs. 800 and 907) is shown diagrammatically in Fig. 1,352. In this type of transformer the windings are concentric, two primary coils being in the middle, with one secondary coil inside next to the core and one outside. Each of these secondaries is halved, and Fig. 1,352 shows that to secure the voltage regulation desired the inside portion of the secondary winding on one side of the primary is connected in series with the outside portion of that on the other side. The result is that the drop of voltage on either side of the secondary under any ordinary conditions of unbalanced load does not exceed the guaranteed drop for working on a two-wire system.

Three-phase Balancers.—In the second, (ii.), application of static transformers as balancers referred to on page 1307 the principle of the auto-transformer is also used, a zigzag winding being adopted. The advantages of using the star-zigzag method of connecting three-phase transformers has already been explained on page 944. The object there was to enable a 400-volt three-phase power load to be supplied from the same mains as single-phase 230-volt lighting loads, the latter loads being placed between a wire connected to the neutral point of the secondary winding of the transformer and one or other of the line wires.

It may, however, happen that the lighting load is a considerable distance from the distributing point where the large transformer is placed, and in that case the above method would require the neutral wire to be run right back to the distributing transformer, thus adding to the cost of the distributing mains. To avoid this the Westinghouse Company place a three-phase auto-transformer in a position conveniently close to the lighting load. The coils of this transformer are split and connected as shown in Fig. 1,353, where it will be noticed that in each phase one-half of the winding is on one limb and the other half on another limb of the transformer. The arrangement is exactly the same as that of the secondary circuits of Fig. 965, and the result is the same, the vector diagram of Fig. 966 being applicable, except that for strict accuracy the magnetising and coreless vectors of the primary should be included, as in all auto transformer diagrams.

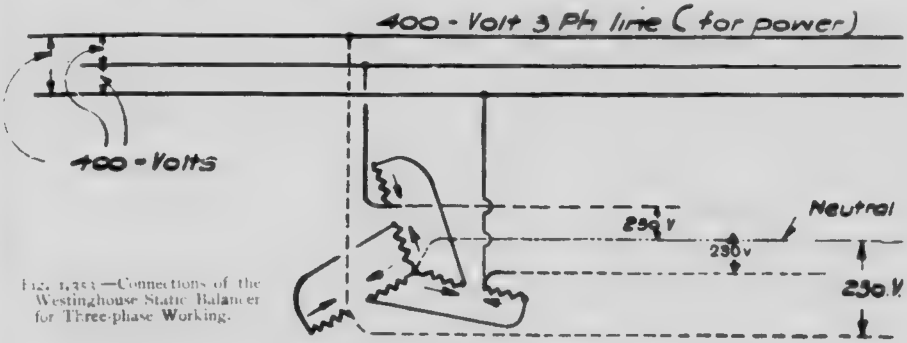


Fig. 1,353.—Connections of the Westinghouse Static Balancer for Three-phase Working.

As the static balancer has only to take charge of the out-of-balance currents, for one terminal of each single-phase load is directly on the mains, it need only be quite small. Thus, it is calculated that a balancer similar in size to a 5-*k*V.A. transformer will deal with a maximum out-of-balance current of 25 per cent. of the full-load current on the outers of a 100-*k*V.A.

circuit with a phase-voltage variation from normal of only one-third of
voltage drop of a 5-*kv.a.* transformer.

With such balancers the large main transformers may be of the
star connected type instead of the more costly and less efficient mesh
type. The saving in cost is more specially noticeable where the
formers are of high voltage or low output.

Static Balancers on C.C Three-wire Systems.- When a continuous-current
three-wire distribution system is receiving energy from ordinary dynam
with their terminals connected to the outers, automatic balancing can
obtained by reproducing as much as is necessary of the rotary convert
system of balancing described above (*see* page 1305). Thus two slip ring
added to the dynamo, as in Fig. 1,354, and connected to points on th
armature windings 180 electrical degrees apart, convert the dynamo int
a single-phase rotary or a double-current generator. The slip ring brushes *b b* are connected through separate leads $l_1 l_2$ to the balancing transformer, which, as in case 1 above, is a 1-to-1 transformer with its coils $s_1 s_2$ in series and with the junction point *j* joined to L_n. When the alternating currents in s_1 and s_2 are equal, that is, when the loads on the two sides are balanced, the point *j*, being midway in potential between l_1 and l_2, is at the potential of L_n and no current flows into L_n from the transformer, which, however, carries single-phase currents drawn from the slip rings. If, however, the loads are out of balance the potential of L_n is no longer midway between the potentials of L_1 and L_2, and current flows to or from the middle wire through the transformer to the dynamo in much the same way as has been described for the out-of-balance currents in a rotary converter similarly used as a balancer.

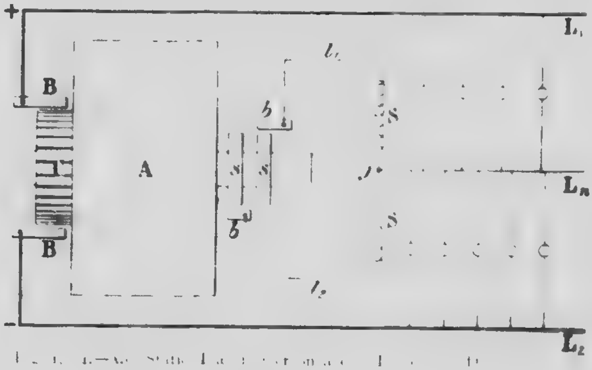


Fig. 1,354.—Static Balancer [illegible]

As in the previous cases the transformer is of small capacity compared with the total power handled. It has, however, to be specially designed for the low frequency demanded, which is that of the currents in the armature of the generator, namely $p \times n$, where p is the number of pairs of poles and n the revolutions per second of the generator. Thus for the 10-pole Brush Electrical Engineering Company's dynamo illustrated in Fig. 161, page 162, the frequency at 504 R.P.M. is 42; for the 10-pole Mather and Platt dynamo, illustrated in Plate II., page 10, it is, at 300 R.P.M., 25 periods; and for the 30-pole 30-R.P.M. dynamo referred to on page [illegible] it is only 7·5 periods per second. The value of the [illegible] voltage applied to the transformer is that of the brushes B B (Fig. 1354), whilst its R.M.S. value is this voltage divided by $\sqrt{2}$ (= 1·414). Because of the low frequency the iron losses will be small, and it is important that the copper losses should also be small so as to assist the equal division of the voltage.

The advantage of using this static balancer as compared with the kinetic transformers (motor generators) referred to at pages 631 to 635 of Vol. I. and at pages 1303 to 1305 above, is that it requires no attention such as must be given to all running machinery. The disadvantages are that it can only be used where the generator is accessible, and that it requires slip-rings to be mounted on the generator; also that the leads for the balancer must be carried back to the generator, whereas the kinetic balancer can be strung across the outers at any convenient point.

Power-factor Control.—Quite frequently in different parts of this book the disadvantages of a lagging current produced by an inductive load have been referred to. The chief of these disadvantages are:

(i.) The increased loss in the transmission lines due to the transmission of the wattless current;

(ii.) The diminished kilowatt output of the generators, requiring the installation of larger plant;

(iii.) The demagnetising effect of the wattless current on the field flux of the generators; and

(iv.) The consequent lowering of the regulating power and the diminished efficiency of the generators.

Causes of Low Power Factor.—The low power factor is in most cases largely due to the inclusion of induction motors in the load; static transformers tend in the same direction but have a smaller effect as compared with their capacity, and A.C. arc lamps also give rise to lagging currents; choking coils have of course a similar effect, but the effect, deliberately introduced, is not considerable in any [illegible] power [illegible].

Remedies.—The most effective remedy would seem to be the partial elimination of the chief cause of the trouble by the improvement of the power-factor of induction motors which in other respects are so convenient for the conversion of A.C. power into mechanical power. Leblanc, Heyland, Miles Walker, and others have worked on this problem with the view of producing an induction motor whose power factor shall be [illegible] over a wide range of load, but the [illegible] of this type which [illegible] adoption has not yet been [illegible]. References are [illegible] on "Induction Motors" [illegible] of the methods of improving the power factor. Attention may be specially called to the [illegible] work on pages 786 [illegible] Dr. Scherbius [illegible], but there are other references throughout the chapter.

Phase Advancers for Induction Motors. The chief cause of the lagging power factor of an induction motor is due to the fact that a large wattless current has to be supplied by the stator for maintaining the magnetic field. In 1895 Leblanc pointed out that if the magnetising current could be supplied by the rotor in which the currents are of much lower periodicity, this cause of the low power-factor would be removed, and if the machine could also be over-excited it might even take a leading instead of a lagging current. To provide such a magnetising current it is necessary to inject a suitable E.M.F. into the rotor circuit by connecting to its slip rings a suitably designed machine which is now known as a phase-advancer. The subject has been developed by Kapp, Miles Walker, and others, but lack of space prevents us from dealing with it in detail. These phase advancers do their work admirably, but there is the disadvantage of an additional piece of moving machinery, which has to be power-driven, though the power required is quite small compared with the capacity of the induction motor served.

Use of Synchronous Motors.—Taking the existence of induction loads giving rise to troublesome lagging currents as a present-day fact, attention has been given to methods of introducing into the distribution system itself leading currents which, when combined with the lagging currents, shall bring the power-factor of the whole to unity value.

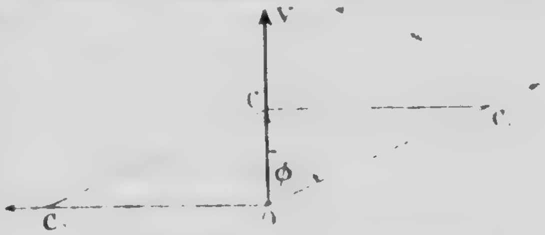
These are also known as phase-advancers, and for this purpose well-loaded synchronous A.C. motors are frequently used. Such a motor is necessarily separately excited (see page [illegible]), and the phase-angle of the current it takes depends upon the excitation. At normal excitation the phase-angle should be 0° and the power factor of the machine unity. If under-excited the motor takes lagging currents, and if over-excited leading currents. The most economical effect is produced when the motor can be well loaded mechanically. The motor, if it is to give large out-of-phase currents, must be larger than if it is to be run at unity power-factor, but it is calculated that a large motor can be designed to give a leading wattless current 60 per cent. of its kilovolt-ampere rating at an increase of only 10 per cent. in its cost. Such a current corresponds to a leading power factor of 0·8.

The self-starting synchronous motor of the Lancashire Dynamo and Motor Company described on page 716 is particularly well adapted to act as a phase-advancer, since the exciter (Fig. 728) can readily be arranged to give the necessary over-excitation and the machine can stand a heavy current overload. It is also self-synchronising.

Use of Rotaries.—These can also be utilised as phase-advancers on the A.C. side, whilst supplying continuous currents on the C.C. side. They have a great advantage over the synchronous motors in their high efficiency and greater synchronising power on heavy overloads. If the field excitation is of the correct value the back E.M.F.S generated in the conductors by [illegible] rotation of the armature are such as to cause the currents referred to on page 980 *et seq.* to be so distributed as to give the proper distribution of motor and generator currents in the different parts in phase with the back E.M.F.s and with the forward driving voltage. In fact the machine will run at unity power factor with currents and voltages in phase.

If, when this state has been attained, the field be suddenly weakened, it is obvious that the motoring currents would momentarily increase and the generator currents diminish, and the machine would tend to run faster, which it cannot do, as it must run synchronously with the periodicity. What happens may be explained from different standpoints. Perhaps the simplest, though the actual action is more complicated, is to regard the armature as acting like a choking coil and setting up [illegible] inductive E.M.F.s in the path of the current. This means a [illegible] and a lagging power factor, which is what actually occurs.

If, however, the field were suddenly strengthened, the generator action would be increased and the motor action would be cut down, and as the speed cannot drop the automatic inductive action must be opposite to that in the previous case, and must alter the phase angle in the opposite sense. In other words the machine must take a leading current to [illegible] the effects of the over-excited field.



[illegible]

By altering the field strength [illegible] is made to act as a phase changer [illegible] leading currents [illegible] is to act as a phase [illegible]

[illegible]

[illegible]

[illegible] current might be used [illegible] as to produce [illegible] phase [illegible] is the impressed P.D. and OC_1 the current through the inductive l[illegible] lagging by the angle ϕ_1 behind the P.D. The current OC_2 is the c[illegible] denser current leading 90° on the P.D. The vector sum or resultant [illegible] C_1 and OC_2 is, by hypothesis, to be in phase with OV, and therefore m[illegible] be the vertical diagonal OC of the parallelogram OC_1CC_2.

The capacity K of the condenser necessary to produce this effect c[illegible] be calculated for a given load of W (watts) at a P.D. of V (volts) and wi[illegible] an angle of lag ϕ_1, as follows:—

$$OC_1 = \frac{W}{V\cos\phi_1} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

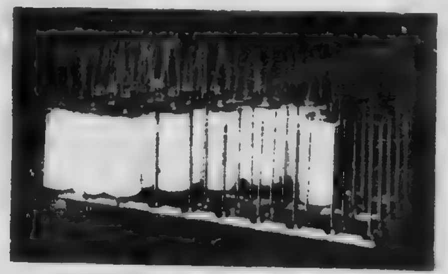
$$OC_2 = pKV \text{ where } p = 2\pi n \quad . \quad . \quad . \quad (2)$$

From the diagram $OC_2 = OC_1 \sin\phi_1 = \frac{W\sin\phi_1}{V\cos\phi_1} = \frac{W}{V}\tan\phi_1$

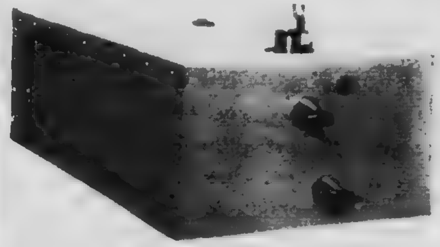
Therefore $pKV = \frac{W}{V}\tan\phi_1$

and $K = \frac{W\tan\phi_1}{pV^2} \text{ farads} \quad . \quad . \quad . \quad (3)$

The required capacity is thus seen to be proportional to the tangent of [illegible]



[illegible] Det[illegible] of [illegible]



[illegible] M[illegible] P[illegible]

[illegible] angle of lag and [illegible] otherwise of delay.

[illegible] difficulty [illegible] in applying these simple results to a practical [illegible] taking [illegible] 75 [illegible] W [illegible] volts and 25 periods with a power factor [illegible]

$$K = \frac{[illegible]\ 52\ [illegible]\ 10^6}{2\pi\ [illegible]\ 650\ [illegible]} \text{ microfarads}$$

[illegible] 75 [illegible]

[illegible] 50π [illegible]

K = 565 microfarads

which is quite a large capacity.

The second difficulty is that through dielectric hysteresis and leakage these large condensers become heated when subjected to rapidly alternating [illegible] and since dielectrics are bad conductors of heat it is not easy to keep the condenser at a reasonable temperature low enough to [illegible] that it will not quickly break down.

Many years ago **Mr. James Swinburne** constructed condensers to act as phase advancers to correct inductive loads but was not [illegible] in overcoming all the practical difficulties. Subsequently [illegible] have endeavoured to solve the problem, and Fig. 1357 [illegible] power-regulating condenser in process of manufacture [illegible] made by British Insulated and Helsby Cables, Ltd. The complete [illegible] built up by assembling a sufficient number of the [illegible] described in the Telephone section [illegible]. The [illegible] connected, as shown, in groups of [illegible] each group being placed in [illegible] as in Fig. 1357. The box is [illegible] the [illegible] weighing 75 lb. and measuring [illegible] inches × 7½ inches [illegible] having eleven [illegible] placed [illegible] 7 cwt.

It will be noticed that the [illegible] proportional to [illegible]

65	18	42	[illegible]
[illegible]	25	50	54
68	36	52	75

[illegible] Table XIX gives the values [illegible] shows that [illegible] 4 [illegible] between [illegible] rapidly.

Insulation Resistance of Networks.

—The maintenance [illegible] networks [illegible] the losses of energy which leakage involves, in view of [illegible] injurious effect of wandering currents which are referred to [illegible]

[illegible] the Board of Trade [illegible]

"6. *Maintenance of Insulation.*—The insulation of every complet circuit used for the supply of energy . . . shall be so maintain that the leakage current shall not under any conditions exceed o thousandth part of the maximum supply current; and suitable me shall be provided for the indication and localisation of leakages. Ever leakage shall be remedied without delay. Every such circuit sh be tested for insulation at least once in every week, and the unde takers shall duly record the results of the testings. . . .

"34. *Connection of Earth of a Three-wire System.*—(*a*) The con nection with earth of the intermediate con ductor shall be made at one point only o each distinct circuit, namely, at the generat ing station, sub-station or transformer, an the insulation of the circuit shall be efficientl maintained at all other points.

"(*b*) The current from the intermediate con ductor to earth shall be continuously recorded, and if it at any time exceed one-thousandt part of the maximum supply current, steps shall be immediately taken to improve th insulation of the system."

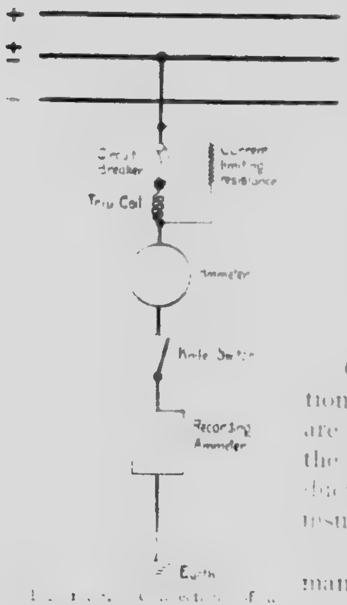


Fig. 1,358.—Connections of a Mid-wire Earthing and Test Panel.

Quite apart, therefore, from other considera tions, the managers of public supply undertakings are under statutory obligations to test periodically the insulation of the distributors, and all con ductors connected thereto, and to maintain goo insulation within certain limits.

These periodical tests render desirable the per manent installation in the power or sub-station o some easily operated testing equipment, an accordingly "testing panels" have been devised with the view of complying easily with the Board of Trade regulations.

The arrangement of such a testing panel is quite simple, as can be ascer tained by inspecting Fig. 1,358, which shows diagrammatically the con nections of a standard mid-wire testing panel, as designed by the Britis Westinghouse Company. The middle wire of the three-wire distributio system is connected to earth through (i.) a circuit breaker with the usual trip coil and current limiting resistance; (ii.) an indicating ammeter; (iii.) a knife switch; and (iv.) a recording ammeter. As the direction of the current may be either towards or from the earth plate, the two ammeters are polarised instruments which indicate the direction as well as the magnitude of the current, and the recording ammeter fulfils one of the conditions in regulation 34 (*b*) quoted above. The knife switch is to disconnect the earth when necessary, either for making some of the tests described later or for any other purpose.

Testing. The Board of Trade regulation quoted above for the "maintenance of insulation" lays down that the mains shall be tested at least once in every week, and this is also desirable for other reasons.

There are various methods described elsewhere in this book for testing the insulation resistance of conductors which are not conveying currents other than the currents used for testing. It is, however, one of the conditions of supplying electric energy for public lighting purposes that the mains shall not be disconnected or become "dead," and a periodical disconnection for merely routine testing would violate this condition. Fortunately, it is not impossible to devise tests for measuring with sufficient accuracy the insulation resistance of "live" circuits, and a few of the simpler tests of this kind may be briefly referred to, more especially the testing of low-voltage two- and three-wire networks whilst not interrupting the supply.

With a two-wire network the simplest test is to measure with a suitable voltmeter of known resistance r the voltage V between the + and − sides of the system, and the voltages V_1 between the + conductor and a good earth and V_2 between the − and the same earth. These tests can be made rapidly and from them the insulation resistances of each wire of the system to earth can be calculated by the equations

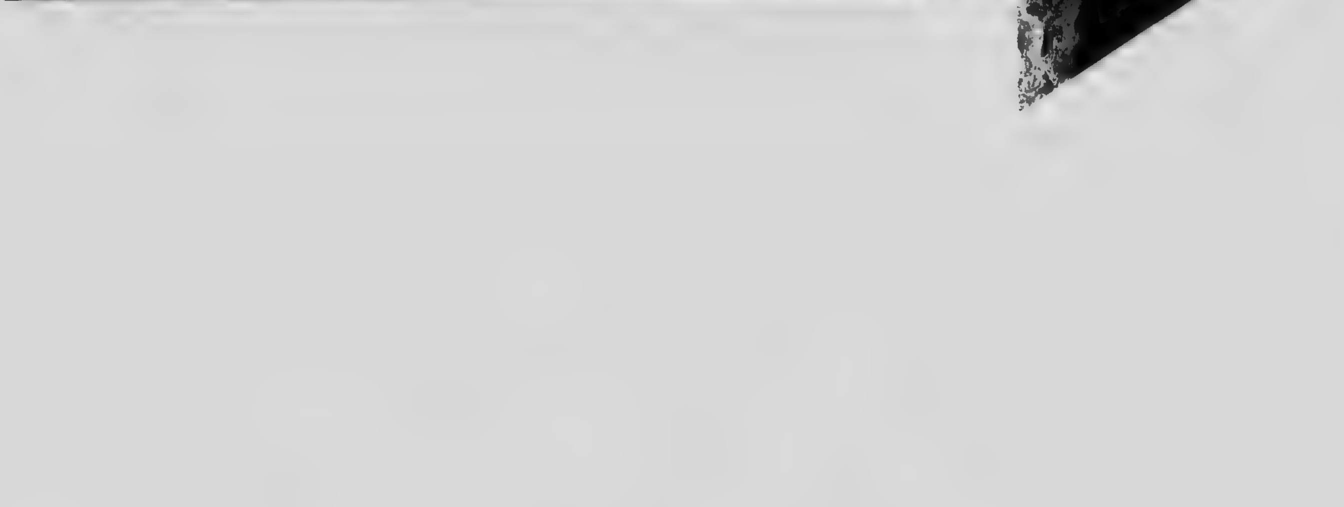
$$R_1 = r\,\frac{V - V_1 - V_2}{V_2}$$

$$R_2 = r\,\frac{V - V_1 - V_2}{V_1}$$

where R_1 is the insulation resistance of the + and R_2 that of the − conductor.

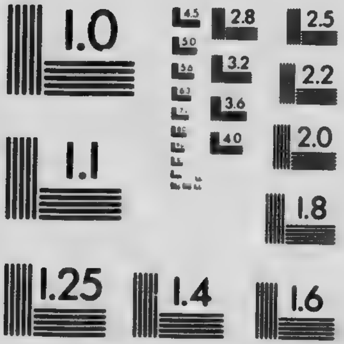
In the three-wire case the network is continually under test if regulation (see page 1316) be complied with. But although a careful study of the daily chart of the recording ammeter placed on the earth connection of the middle wire gives valuable information, and would at once reveal any sudden serious and local change in the insulation resistance, the currents recorded are the differences of various leakage currents, and do not by themselves give a test from which the actual insulation resistance can be calculated. For instance, in the improbable case of exactly similar and serious faults developing at the same time on the + and − outers, the recording ammeter would give no indication. Other tests, either supplementary or quite different, are therefore necessary.

One of the simplest of these was worked out by Dr. A. Russell and communicated to the *Institution of Electrical Engineers* in 1900. The current from the middle wire to earth is momentarily interrupted by a switch S (Fig. 1,359), and the P.D. (v_1) between that wire N and the earth measured on



MICROCOPY RESOLUTION TEST CHART

(ANSI and ISO TEST CHART No. 2)



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Rochester, New York 14609 USA
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(716) 288 - 5989 - Fax

a voltmeter V; the circuit is again made through a known resistance (r and the P.D. (v_2) again measured, or the current (i) passing to earth i measured on an ammeter A. If now the insulation resistance be denot by R, it can be shown that—

$$R = r\frac{v_1 - v_2}{v_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

whence

$$R = \frac{v_1}{i} - r \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

or

$$v_1 = i(R + r) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

from which the value of R can be readily calculated, the resistance r including the resistance of the ammeter. Objection has been made to this test because it removes the earth from the middle wire for the few seconds necessary to obtain the first reading v_1 of the voltmeter, and by so doing alters the potential of the middle wire. The alteration, however, besides being of short duration will not be very great in most cases in practice. There is the additional objection that there may be a great change in the insulation resistance whilst the switch is open, but this is not very probable.

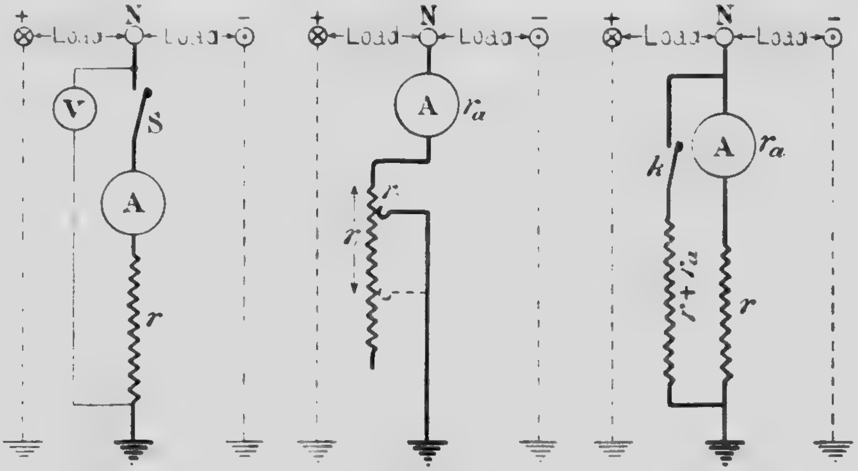


Fig. 1,359. Fig. 1,360. Fig. 1,361.

Methods of Testing the Insulation Resistance of a Three-wire "Live" Network.

To get over the difficulty of breaking the earth connection, however, Drs. Kapp and Coales in 1909 proposed to take two readings of the ammeter A (Fig. 1,360) with different values of r_1 and r_2 of the resistance r so adjusted that the current in A with the smaller resistance (r_2) in circuit is exactly double that with the resistance (r_1) in circuit. These tests lead to the equations—

$$E = i_1(R + r_1 + r_a)$$

$$E = 2i_1(R + r_2 + r_a)$$

whence $$2(R + r_2 + r_a) = R + r_1 + r_a$$

and $$R = r_1 - 2r_2 - r_a \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where r_a is the ammeter resistance, which is not inappreciable since the instrument must be one for reading small currents and should preferably be of such sensitiveness that the larger current gives nearly the full deflection. The test resistances r_1 and r_2 should be obtained from a graduated resistance with a sliding contact.

Another well-known test with the same object is Raphael's (Fig. [illegible]), in which the ammeter and the resistance r in series with it are, after the current i has been read, shunted with a resistance of equal value and the current (i_2) through the ammeter again read. In this case the equations are :—

$$E = i_1(R + r + r_a)$$

$$E = i_2(2R + r + r_a)$$

whence $$2Ri_2 + ri_2 + r_a i_2 = Ri_1 + ri_1 + r_a i_1$$

$$R(2i_2 - i_1) = (r + r_a)(i_1 - i_2)$$

$$R = (r + r_a)\left(\frac{i_1 - i_2}{2i_2 - i_1}\right) \quad . \quad . \quad (4)$$

$$= (r + r_a)\left(\frac{d_1 - d_2}{2d_2 - d_1}\right) \quad . \quad . \quad (5)$$

Equation (4) shows that only the *ratio* of the currents need be known, and therefore, if the galvanometer be graduated so that its scale readings are proportional to the currents passing, its deflections, (d), may be substituted for the actual currents and equation (5) used instead.

The two last-named tests, Kapp's and Raphael's, are open to the second of the objections to Russell's, namely, that, as two readings have to be taken, should the insulation resistance R change appreciably between the first and the second reading, the test is vitiated.

Each of the tests measures the total insulation R of the network, but, if the result is low, gives no indication as to the part of the system +ve, −ve, or neutral, on which a serious fault has developed. In this case it is desirable to test, if possible, the insulation resistance R_1 of the +ve and that of R_2 of the −ve sides separately, and also the insulation resistance R_0 of the neutral wire when not connected to earth.

The most important of these three insulation resistances, R_1, R_0, and R_2, is R_0, that of the neutral wire, because a serious breakdown of insulation on either of the outer wires would be indicated by an increase in the current through the recording ammeter in the earth connection of the neutral wire. Dr. Kapp and Dr. Coales, in the paper already referred to, show how these resistances may be measured by taking advantage of the Board of Trade regulation, which allows a variation of ± 4 per cent in the pressure on the consumer's premises. The test consists in first of all keepin the voltage (V) between the outers quite constant during the period of th test, and in altering the voltage between the outers and the middle wir so that in the first test the higher voltage is on the +" side, and in th second test this higher voltage is on the −" side. The low readin ammeter, A in Fig. 1,360, is, with its series resistance, kept in circui during the two tests, and the voltage between N and earth is measure either directly or indirectly. With these data and a knowledge of the insulation resistance R of the whole system as ascertained by one of th previous tests, or an equivalent test, the resistances R_1, R_0, and R_2 can b calculated.

Automatic Sub-stations.—The apparatus installed in some of th types of sub-stations described in this chapter is so simple that its operation with automatically acting regulators in the sub-station itself, together with remote control from a distant point, such as the switchboard of the generating station, is evidently a problem which may not present insuperable difficulties. Especially would this be the case in sub-stations containing only static transformers, but where there is rotating machinery, successful operation without the presence of attendants in the sub-station is not quite so obvious.

The problem, however, has been successfully solved during recent years, more particularly in the case of sub-stations on transmission and distribution systems supplying power for electric traction. As the conditions are somewhat special, it will be more convenient to postpone further reference until we are dealing later with the whole subject of "Electric Traction."

CHAPTER XIII

PROTECTIVE GEAR FOR ELECTRIC CIRCUITS

THE development of the utilisation of large quantities of electric power for industrial and other purposes has brought into prominence a number of problems due to the necessity for safeguarding the disastrous consequences which may ensue if, through any breakdown in the insulating or other devices, dangerous currents or voltages should be developed at any point or points on the circuit. With such large sources of power available the energy which, as a consequence, may be very rapidly concentrated locally may be destructive in quantity, and as it usually appears in the form of heat may, even if small, start a chain of events which may quickly lead to most serious results. The danger, as may be readily supposed, became evident from untoward experience as soon as the sources of electric power employed assumed engineering dimensions. Even earlier, when the currents used were quite small and only employed for signalling purposes, the necessity for guarding against lightning discharges which threw energy into the circuits from external sources had to be recognised.

The particular precautions taken for safeguarding telegraph, telephone, and similar circuits will be more conveniently described in connection with those applications of electricity to the service of man. This section will therefore be confined to the precautions adopted for protecting circuits generating, transmitting, distributing, or utilising electric power on an engineering scale.

The causes of trouble may either (i.) lie within the circuit itself or (ii.) be external to the circuit. When within the circuit, they can usually be traced to failure of insulation resulting in short circuits, earths, or other faults, and sometimes to disconnections, resulting in dangerous arcs being struck across the gap and the rapid development of serious consequences. Such failures of insulation may be caused (*a*) by sudden variations of load, (*b*) by faulty operation of apparatus, or (*c*) by opening and closing circuits without proper precautions against surges. The simplest and most frequent remedy for a breakdown of insulation, rapidly developed, is to bring into play, automatically, some kind of protective gear or "cut out" which will "break the circuit" and thus cut off the faulty part of the circuit from the generating source from which a dangerous supply of energy would then be drawn.

In the second case, the external source of the mischief may be a lightning discharge or a leakage from a neighbouring circuit which, especially in th case of lightning, may be conveniently dealt with by providing a suitab alternative path or paths for the foreign energy, thus keeping unaffecte the circuit which is to be protected. Dangerous static charges due t atmospheric causes may also accumulate on overhead wires.

I.—FUSES

The earliest form of protection from dangerous currents drawing thei energy from the generators of the system is the *safety fuse* or fusible "cut out," an early form of which is shown in Fig. 1,362. The principle is doubtless thoroughly familiar by this time to most people. A short length of easily fusible conductor of much higher resistance *per unit length* than the neighbouring conductors, and technically known as a *fuse*, is inserted in the circuit. The fuse is of such dimension and material that whilst capable of carrying the normal maximum current without becoming hot, it will fuse, or "blow," as it is called, when the current passing reaches a predetermined and assumed dangerous value above the normal maximum.

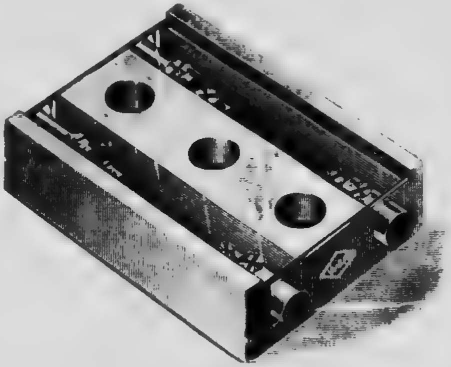


Fig. 1,362.—Double Pole Cut Out.

This very simple principle requires in its practical application the observance of a number of simple precautions, some of which are quite obvious, and others less so. The properties of a good fuse may be briefly summarised as follows:—

It should be so mounted that when it "blows" a dangerous arc cannot be formed by the voltage available.

It should "blow" promptly as soon as the current for which it is set is reached, whether the current in the circuit is being increased rapidly or slowly.

It should not blow *before* the dangerous current is reached.

It should be so mounted as not to become dangerous if maintained below the blowing temperature for a long period.

The fused metal, when it blows, should not be a source of personal, or of fire, danger

It should be so designed and mounted as to be readily replacable by a new fuse when it blows.

It should not alter by effluxion of time under ordinary external conditions or by repeated safe heatings and coolings in service.

Fuse Materials.—The *metals* usually employed for fuses are copper, tin, or lead, whose specific resistances, cold, are 1·65, 13·36, and 20·3 microhms (cm. measure) respectively (*see* page 751, Vol. I.). Of these *copper* has the disadvantages of being a good conductor of both electricity and heat, and has a high fusing temperature (1,083° C.); it is not readily oxidised, is fairly permanent in service, and easily procurable. *Tin* has about eight times the specific resistance of copper, a low melting point (232° C.), which is much below a red heat, and is also flexible; at temperatures approaching its melting point it is, however, readily oxidised by the atmosphere, and the layer of oxide is, if thick enough, sometimes sufficiently coherent to enclose the molten metal without breaking, thus keeping the circuit intact with currents above the fusing current. *Lead* has over twelve times the specific resistance of copper and melts at 327° C., which is also below a red heat; it is very ductile and not easily acted upon by the atmosphere.

The fusing current for a particular material is dependent on the length and gauge of the wire used and the holder in which it is mounted. For instance, for different types of holders Messrs. Ferranti, Ltd., give the approximate fusing current of a No. 20 (36 mils) s.w.g. tinned copper wire at 45, 50, or 70 amperes. As the last-named current is nearly double the first, it is obvious that the design of the fuse-holders as well as the gauge and conductivity of the fuse wire must be carefully considered.

Fuse-holders.—Even, however, when constructed with a full knowledge of the requirements, the production of a fuse and fuse-holder which shall be reliable under all conditions of service is not an easy matter. The attainment of the melting temperature when the dangerous current passes must obviously be a matter of time, which may be affected by a change in the local conditions. For instance, a change in the ventilation, if it carries away heat more quickly, will retard the blowing of the fuse. Then again, if the fuse has been oxidised by having been exposed to the atmosphere for many months or years, its resistance will be increased, more heat will be produced by a given current, the layer of oxide will tend to retain this heat in the metal, and the fuse may blow before the dangerous current is reached. Still further, the connections to the terminal blocks may become loose, leading to local heating and premature blowing. The terminal blocks themselves, through being too massive or through the fuse being too short, may conduct away so much of the heat that the attainment of the fusing point may be appreciably delayed on a slowly rising current or unless there is a great excess of current. Thus, on the one hand, the breaking of the circuit may be delayed until serious damage has been done somewhere in the circuit, or, on the other hand, the circuit may be opened prematurely, causing annoyance or even danger from the sudden lightening of the load on a small generating plant.

From all this it follows that wherever the importance of the circuit or part of the circuit to be protected justifies it, some more reliable form of "cut-out" should be employed. There remain, however, many cases in which a fuse is the only *practical* solution from considerations of expense.

The cases in which fuses are most widely used are on the premises of consumers, whether domestic or industrial. In such cases it is usually an official regulation that the entering mains shall be protected by fuses, and further regulations require the similar protection of subsidiary circuits.

The following figures, selected from a large number of good designs which are available, will give the reader a fair idea of the appliances used in connection with this method of protecting circuits by fusible cut-outs. The complete apparatus consists of two parts: (i.) the base, which provides (*a*) the terminal blocks [illegible] the conductors of the circuit are permanently attached, and (*b*) a fitting for the attachment of the fuse proper; and (ii.) the actual fuse, which is sometimes a piece of bare wire, cut as required to the necessary length, but is more frequently separately mounted more or less elaborately in a special fitting.

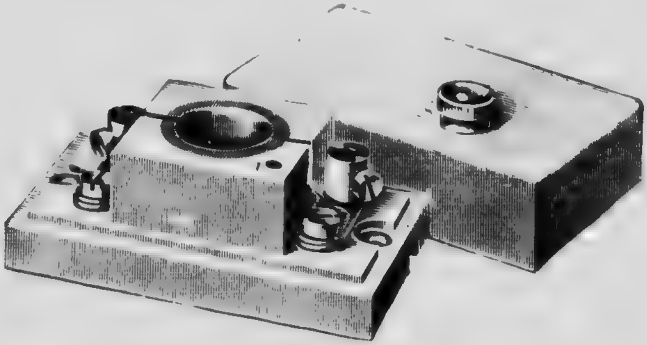


Fig. [illegible].—Fuse-holder for a Protected Fuse.

Fuses for Small Currents.—The current which a fuse is intended to carry obviously must affect its design, and that of the holder in which it is to be placed. For small currents of, say from 5 to 20 amperes, the fuse is often contained in some other fitting, such as a switch, a ceiling rose or a wall plug, and in these cases its mounting will be most conveniently described in connection with such fittings. Separate fuse-holders are, however, standardised for these currents and may be briefly referred to.

The design is often such as to afford some protection for the fuse wire which will render it less susceptible to the cooling effects of currents of air, and at the same time make it more difficult for an arc to be set up or maintained across the gap when the fuse blows. This protection is furnished by a modification sometimes of the base and sometimes of the fitting which carries the fuse wire. An example of the former of these alternatives is shown in Fig. 1,363 of a cut-out made by the General Electric Company, of London. The fuse base, including the central projection, is made of vitreous china. This projection contains a cylindric fuse chamber lined with a refractory material which does not crack when heated and tends to quench any arc which may be formed. The fuse wire is shown in position entering the chamber through slots in the china projection. As the ends of the wire would be cooled by the terminals the break on fusing will most probably take place within the lined chamber. The detachable cover is clamped on to the base by the screw s entering the threaded hole *a*.

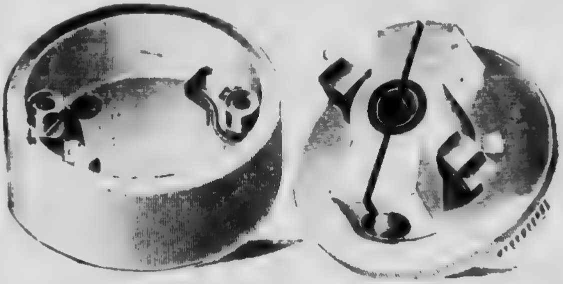


Fig. 1,363.—Refractory-lined Chamber Cut-out

Another method is to place the fuse and the refractory chamber on the cover as shown in Fig. 1,364, in which the base, on the left, contains two fixed spring contacts *c c* connected to the circuit. The cover has two sliding spring contacts c′ c′ attached to the ends of the fuse wire and when this cover is placed over the base and given a half-turn these slide on to *c c* and complete the circuit through the fuse wire. This modification is very convenient if the fuse holder has to be placed in an awkward position which would make it difficult to replace the fuse wire in the pattern shown in Fig. 1,363.

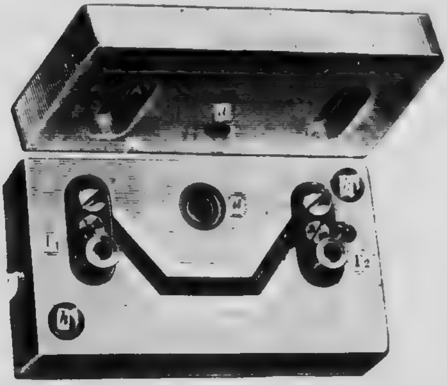


Fig. 1,365.—Fuse-holder (open) showing Fuse Chamber

Still another and neat method of providing for the fuse a narrow, closed chamber of a simple design is shown in Fig. 1,365, in which the path for the fuse is much longer than the distance between the terminals and is lined with a special refractory material, the body of the fuse holder being made of china. The holes *h h* are for screwing the base to its support and the holes *a a* provide for the screw which clamps the cover to the base. One of the circuit leads is brought to its terminal T_1 through the recess *r*, the terminal T_2 being reached through a similar recess on the right.

The fuse-holders in Figs. 1,364 and 1,365 are intended for currents not exceeding 10 amperes, but the fuse-holder in Fig. 1,363 is made for current up to 30 amperes.

Reliable and very well insulated fuses for small currents are required in high-voltage transmission work. For instance such fuses are required to protect the high-voltage circuits of potential transformers, which, it will be recalled, are bridged across the transmission lines and take very small currents at full load. For this case Messrs. Ferranti use the "cartridge" type, as shown in Fig. 1,366, in the form of a very fine "Eureka" (alloy) wire contained in a glass tube. The wire is No. 42 S.W.G. (4 mils in diameter) and, except for about ¾ inch in the middle of the tube, is embedded in an arc-extinguishing powder. The fuse illustrated is designed for current at 12,500 volts and under, the distance between the centre lines of the supports being 9 inches.

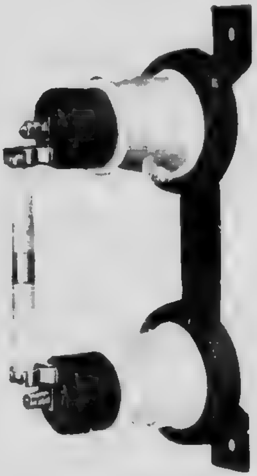


Fig. 1,366.—Ferranti High-voltage Fuse, Cartridge Type.

Time-limit Fuses. Another case in which comparatively fine fuses are required on heavy power circuits is in delaying the operation of the tripping coils of oil switches (*see* page 500). In this case the fuse does not open the main circuit, this being done when a dangerous current passes by the big switch acting as a circuit breaker. The fuse is placed in parallel (not in series) with the tripping coil, through which, therefore an operating current cannot pass until the fuse "blows." The tripping coil is usually fed from a current transformer, and does not directly take the main current. The Ferranti fuse for this case is shown in Fig. 1,367. It is again a "cartridge" fuse consisting of a copper fuse wire about 1½ inches long in a glass tube A which is provided with metal contact ends which can be clipped in the spring jaws B as shown. The jaws are so shaped that the cartridge cannot be shaken out even under excessive vibration.

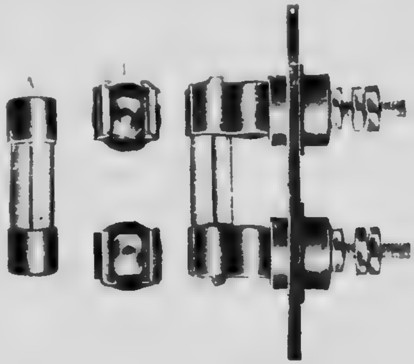
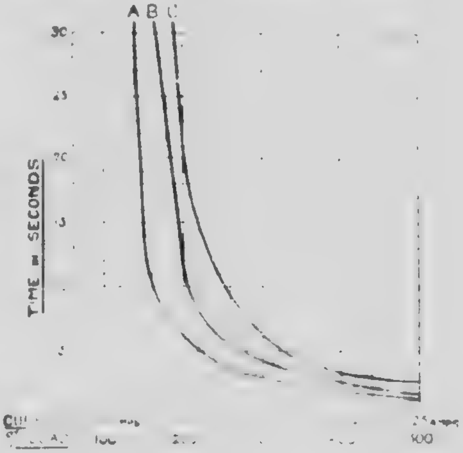


Fig. 1,367.—Ferranti Time-limit F

The rapidity with which the fuse blows depends upon the excess of current passing, and in this connection the curves in Fig. 1,368 are published by Messrs. Ferranti. They show the connection between the over-load current and the time in seconds which the fuse takes to blow, the three curves, A B and C, being for wires of No. 21 (32 mils), No. 20 (30 mils) and No. 10 (40 mils) gauge respectively. The normal load is 5 amperes, at which of course, none of the fuses "blow," and the current transformers on the high-voltage circuits are so arranged that this current in the secondary corresponds to full-load current in the primary or main circuit. At double current the fuses hang fire for 6, 12, and 21 seconds respectively, whilst at five times the full load they only delay the action of the coil by 1, 1½ and 2½ seconds. Thus, for heavy excess currents the safety device acts practically simultaneously, but for less heavy currents it acts more and more slowly. In these latter cases, if the excess current, as it sometimes happens, does not persist long enough, the circuit is not broken, and thus all the inconvenience of a completely broken circuit is [illegible] sufficiently transient.



Fuses for Heavier Currents. The main [illegible] electric power, the circuits of small motors [illegible] heavier currents [illegible] by fuses [illegible] contained in special boxes [illegible] designed to be fixed on a distribution board. [illegible] the designs is very great.

H[illegible] *F*[illegible] usually require, among their conditions, that these fuses shall be in a fireproof box, a condition not difficult to satisfy.

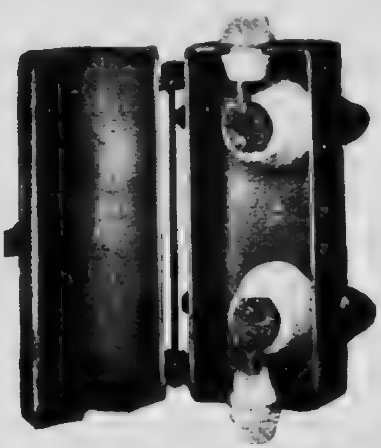


Fig. 1,369. Heavy Service Steel Fuse-holder

A simple form of such a steel fuse-holder is shown in Fig. 1,369, which illustrates a standard pattern made by the General Electric Company, of [illegible]. The metal parts are carried on porcelain pedestals, and the whole is enclosed in a cast-iron box which is lined with asbestos and can be locked up and sealed if desired. The fuse may be of bare copper wire attached to the small terminals shown asbestos-covered copper wire supplied of the correct length and with stamped metal ends, as shown in Fig. 1,370, for ready clamping under the terminal screws. The use of such stamped ends is obviousl better than twisting a bare wire round the terminal. The covering of the wire with incombustib material makes the fusin point independent of current of air, and tends to ensur the "blowing" with the predetermined current.

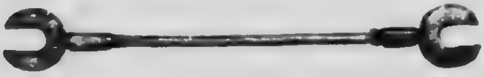


Fig. 1,370.—Asbestos-covered Fuse.

More elaborate protection of the fuse wire is provided in the "cartridge" type of fuse, already referred to on page 1326; another exampl is given in Fig. 1,371. In this type of fuse the wire is contained in a "fuse chamber" made of non-conducting material. In some patterns this chamber is partly filled with a powder which effectively quenches any arc which may be momentarily started.

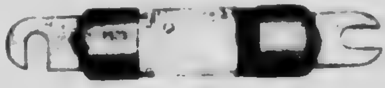


Fig. 1,371. "Cartridge" Fuse.

For house service the supply cable may be of the concentric type whereas the house may be wired with ordinary insulated single wires. In such a case the main fuses may be contained in a fitting which serves the same purpose as the "cable terminals" already described elsewhere (see page 1180). Such a fitting, as made by the General Electric Company, of London, is shown in Fig. 1,372. The concentric cable enters at the bottom and its two conductors are connected to the ring and socket respectively. These conductors are led to the lower terminal blocks of the two single-pole fuse bases shown. The fuse is attached to the jaws of the detachable fuse-holder H shown on the right; these flexible jaws slip on to the terminal blocks and complete the circuit. The fuse is shown in position in the left-hand compartment

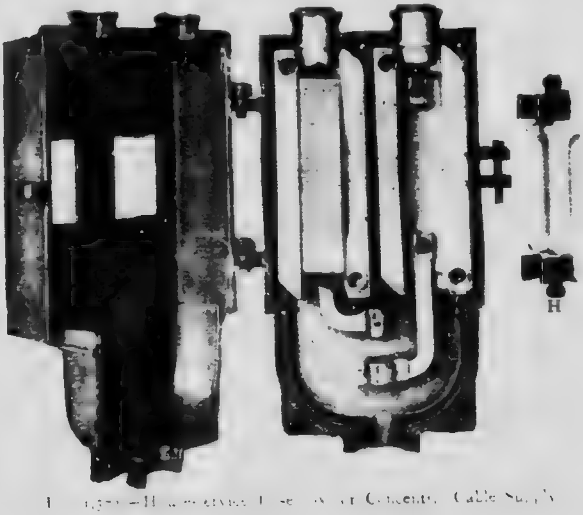


Fig. 1,372.—House-service Fuse Box for Concentric Cable Supply.

Standard sizes up to a carrying capacity of 200 amperes are made of the cut-out shown in Fig. 1,370, and up to 100 amperes for that shown in Fig. 1,371.

Switchboard Fuses. The patterns of fuses designed for mounting on switchboards are almost infinite. At one end of the series they consist of simple blocks of metal mounted on the board between which any piece of wire which happens to be handy may be placed. Such devices have all the defects of the fusible cut-out with the advantage only of cheapness and convenience. At the other end there are elaborately designed bases and fuse-holders, in which are embodied all, or nearly all, the precautions which experience has found to be necessary in minimising the various disadvantages and dangers to which the fusible cut-out just referred to is liable. As before, space can only be found for brief references to typical examples.

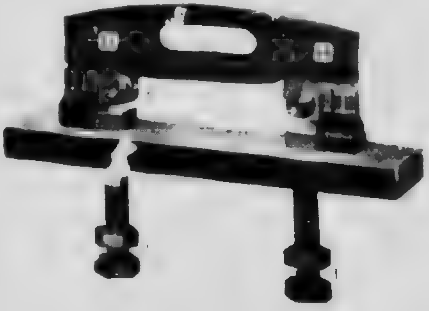


Fig. 1,372.—Wedge [illegible]

A simple form of switchboard fuse-holder made by the General Electric Company for bare or asbestos-covered wire fuses, is shown in Fig. 1,372. It is made of a carrying capacity up to 200 amperes. The jaws of the fixed terminals are similar to the sockets of a "knife" switch, and the fuse terminals are wedge shaped and are forced home into these sockets. The handle H H carrying these wedges is of insulating material, and shields the hand should the fuse blow while the contacts are being inserted in the base. The fuse wire is attached to the screws *f f*, the distance between these screws being about 5 inches for the 200-ampere size. The fuse-carrying terminals attached to the handle are, of course, withdrawn from the sockets during this operation.

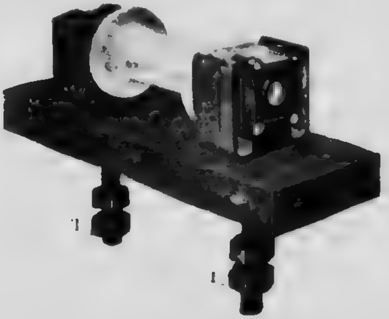


Fig. 1,374.—"Bobbin" Fuse and Fuse-holder.

A more elaborately protected cut-out, made by the same firm, is shown in Fig. 1,374, and is known as the "Bobbin" cut-out from the shape of the porcelain handle through which the fuse wire runs. This handle is tubular and has a concentric tube of solid asbestos running through it. The base carries flexible contact jaws of copper, which are connected to the back terminals T_1 T_2 shown. The ends of the bobbin are squared and covered with copper to slide in the contact jaws. For sizes above 100 amperes capacity the ends are further provided with metal plates for clamping the fuse wires. The bobbins are made to carry working currents up to 600 amperes, and it is interesting to note that for the largest size the clear length of fuse wire between the end plates is nearly 11 inches, and that the fuse wire used consists of four strands of No. 12 S.W.G. of tinned copper wire. This is to carry up to the normal current of 600 amperes, and should blow with a current of about 1,200 amperes.

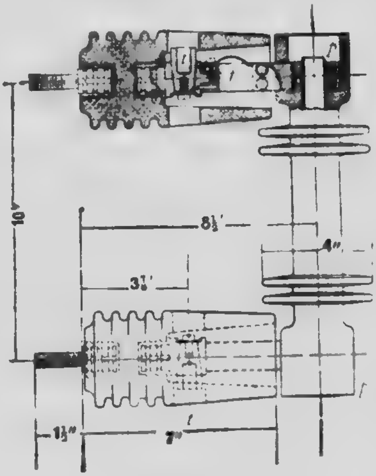


Fig. 1,375. High-voltage Fuse-holder and Fuse.

A modification of this fusible cut-out for high-voltage work is shown partly in section in Fig. 1,375. The two corrugated porcelain pillars are screwed into a slate base which is not shown. The connection terminals *t* are on the front in this pattern, but in another pattern they are behind the board. The flexible contacts for the bobbin are mounted on iron supports and are shielded by cylindric projections of the porcelain through openings in which the thimbles at *t* are reached. The place at which the fuse enters the core of the bobbin is also shielded by porcelain projections *p p*. Dimensions are given, and the fuse is to carry a normal current of 50 amperes at 6,000 volts or a current of 100 amperes at 3,000 volts.

Messrs. Ferranti's fuse for 6,600-volt circuits is shown in Fig. 1,376. All metal parts are carefully "shrouded" with high-class porcelain, and the fuse wire is of tinned copper contained in an asbestos tube inserted in the handles. Only one size of fuse-holder is made, different gauges of wire being used for different normal loads. The length between the centre lines of the columns is 9 inches, which gives a long break. The holder is used for normal currents up to 50 amperes with wires from No. 33 (10 mils) to No. 18 S.W.G. (48 mils) blowing, in this holder with currents of about 10·2 and about 107 amperes respectively. The last-named corresponds to a full load of 700 kilowatts at unity power factor.

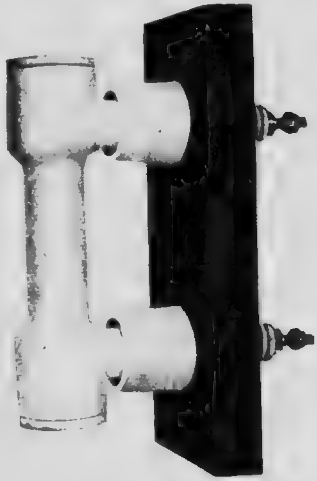


Fig. 1,376.—Ferranti High-voltage Fuse-holder

Switch Fuses.—The danger involved in replacing a fuse which has "blown" is minimised by combining the fuse with a switch, which must be opened before the blown fuse can be replaced. This ensures that the part of the apparatus carrying the fuse shall be "dead" before it can be touched by the operator. A simple form of "switch fuse," manufactured by Messrs. A. Reyrolle & Co., of Hebburn-on-Tyne, is shown in Fig. 1,377. The switch, which is enclosed in an iron box, is shown open, with a simple type of fuse in position in the lid which opens downwards; the fuse is so mounted that when the lid is closed it closes the circuit through the line contacts fixed permanently in the box attached to the panel or wall, and the fuse cannot be handled whilst in contact with the circuit.

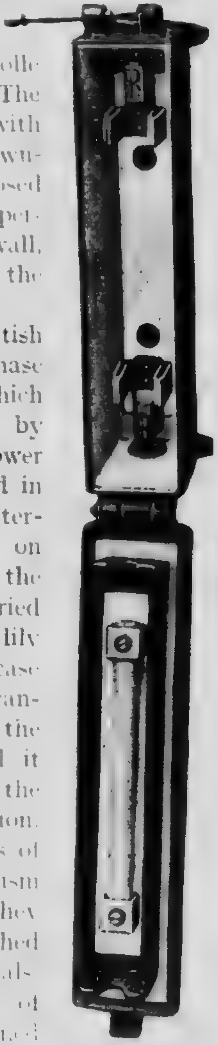


Fig. 1,377.—Reyrolle Single-pole Switch Fuse.

Another pattern of switch fuse, as made by the British Thomson-Houston Company for a 60-ampere three-phase circuit, is shown in Fig. 1,378. The upper part, which is fixed, carries the line contacts, which are separated by insulating partitions to prevent arcing across. The lower part is a cast-iron box hinged to the upper part, and in it the fuse clips and terminals are mounted on porcelain bases. All the movable parts are carried in this box, and are readily accessible when the case is open. The cover cannot be opened until the circuit is broken, and it cannot be closed with the fuses in the "on" position. Consequently no parts of the fuses or mechanism can be touched until they are quite detached from "live" metals. The switch can of course be opened and closed without opening the box, but it can only be left full on or full off, and is locked in either of these positions.

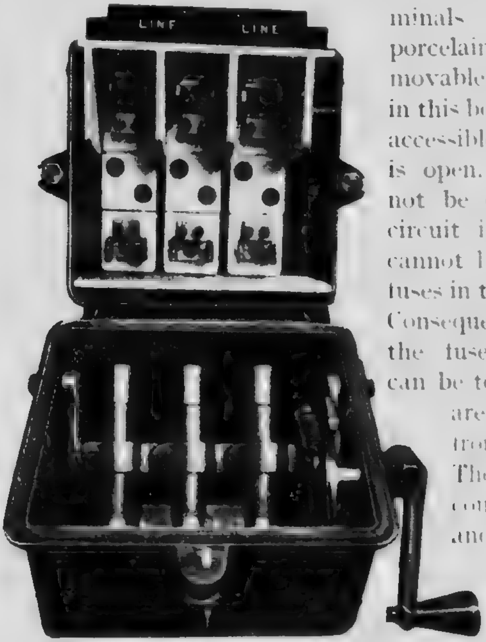


Fig. 1,378.—B.T.-H. Triple-pole Switch Fuse.

II.—CIRCUIT-BREAKERS

Whatever the design may be or the additional apparatus added for special purposes, a fuse, although a convenient, is a somewhat crude form of breaking a circuit in which a dangerous current has been developed. Much ingenuity has therefore been expended in designing switches which shall automatically break the circuit when the dangerous conditions which are to be guarded against have been set up. Such switches are known as "circuit-breakers," or, more shortly, as "breakers."

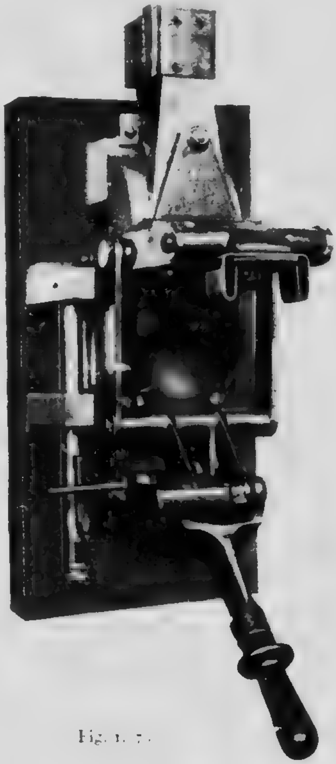


Fig. 1309.

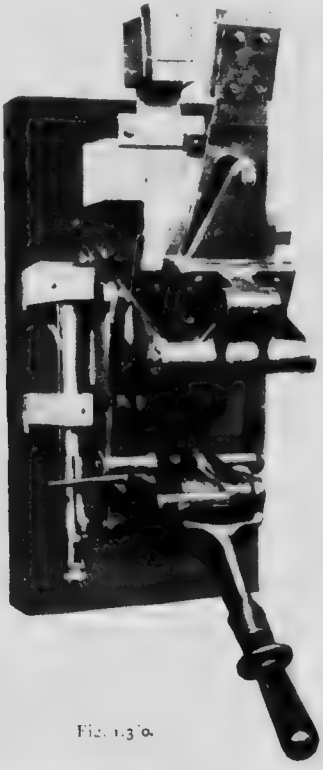


Fig. 1310.

British Thomson Houston Standard Circuit-breaker.

Safety devices of this nature, though not under these names, have been already described in other parts of this book. For instance, in the chapter on C.C. Motors the section on "working" (pages 656 to 686) has many references to such devices. Also in the chapter on A.C. Motors, devices with similar functions are incidentally described at pages 724 and 731. Still more relevant are the tripping coils in connection with the oil switches described on pages 567 to 574 at the end of the chapter on Generating Stations. These coils convert the switches into excellent circuit breakers.

With these examples and others at hand for reference, it is less necessary here to describe in detail any additional type of circuit-breakers, and we shall therefore confine ourselves to one such description, selecting for the purpose, almost at random, one good circuit-breaker out of a great number which are equally well worth describing.

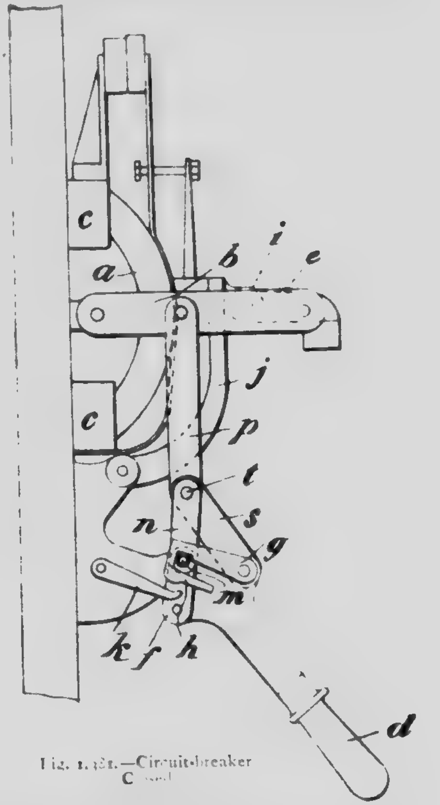


Fig. 1,380.—Circuit-breaker Closed.

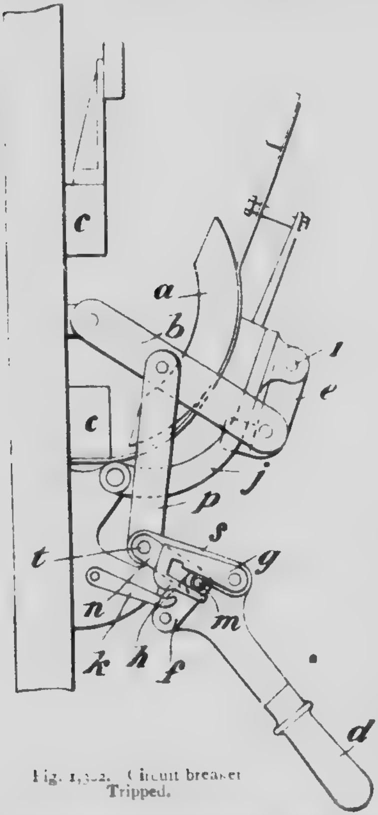


Fig. 1,379.—Circuit-breaker Tripped.

The "breaker" shown in Figs. 1,379 and 1,380 is a well-known type (V. B.), manufactured by the British Thomson-Houston Company. The mechanism by which the switch is closed—an operation which must be performed by hand—consists of an ingenious system of linkages which includes two "toggle" joints, which are straightened out as the handle is depressed for closing, and one of which is held straight by a pin falling into a notch in a loose link. This loose link is knocked aside by the electro-magnetic mechanism brought into play when the switch has to be opened automatically; the holding-pin being thus released, the toggle collapses, the other toggle following suit, and the movable contacts fall away from the fixed contacts by the action o gravity.

It is not possible to pick out from one or two photographs the detail of the linkages; these details are more easily explained by such diagrammatic drawings of the circuit-breaker as are given in Figs. 1,381 to 1,38 which exhibit the switch in three salient positions, in each of which th same reference letters are used. In Fig. 1,381 it is shown closed, th laminated bridge-piece *a*, which is clearly seen in the photographs (Figs. 1,379 and 1,380), connecting the blocks *c c*, which are the fixed electrodes o the circuit to be closed. In Fig. 1,382 the breaker is shown with the parts in the relative positions they occupy after the breaker has been automatically opened, and Fig. 1,383 similarly shows the same parts as placed when the breaker has been re-set for closing by the depression of the handle *d*.

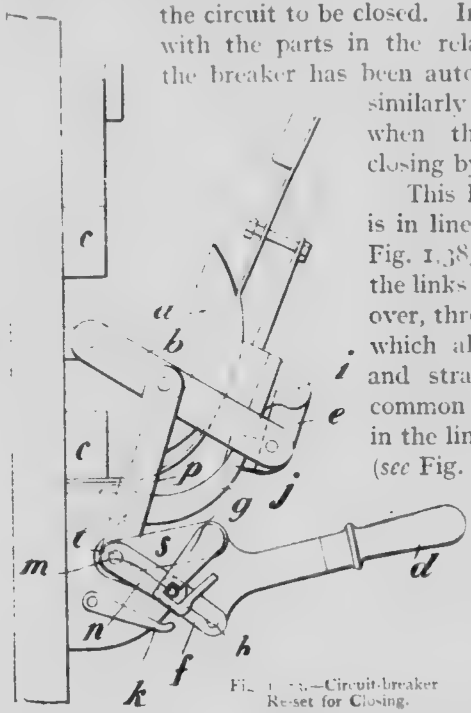


Fig. 1,383.—Circuit-breaker Re-set for Closing.

This handle *d* moves on an axle which is in line with the position of the pin *m* in Fig. 1,383, and carries pins for the ends of the links *s* and *f*. As it is depressed it pulls over, through *s*, the lower end of the link *p*, which also carries one end of the link *n*, and straightens out—by means of the common pin *m* held firmly in the groove in the link *g*—the toggle formed by *n* and *f* (*see* Fig. 1,381). Meanwhile, the link *p* has also been forced upward and has straightened, as seen in Fig. 1,381, the toggle formed by the links *b* and *e*, the former of which is pivoted to the fixed framework. This has forced the bridge-piece *a* against the fixed contacts *c*, thus closing the circuit.

The operation of opening the circuit can be ascertained by comparing Figs. 1,381 and 1,382. The lever *k*, moved smartly upwards by an electro-magnet core or armature, knocks the link *g* upwards, thus partly releasing the pin *m*, so that it moves to the right and downwards in the groove of *g*. This—assisted by the dead weight of the bridge-piece and its mountings—causes the toggle joint between *n* and *f* to collapse, and the quickness of the break is further assured by the collapse of the toggle-joint between *b* and *c*.

The striker *k* operates when the particular contingency to be guarded against arises, and where large currents are being handled its electro-magnet is usually placed in a relay circuit. Thus it can be arranged to trip the breaker when there is an overload or a reverse current, and with or without time-limits. A low-voltage device can also be attached to operate when the line voltage drops to, say, 50 per cent. of the normal. Relays for these purposes will be described presently.

When the switch has been opened automatically, if it be re-set and closed before the danger has passed away, it cannot be held closed by the handle *d*, for the striker *k* will immediately operate and the breaker will again break the circuit.

The bridge-piece *a*, as can be seen in the photographs, is made of laminated copper to give it a certain amount of flexibility and to ensure good contacts. To preserve these metallic contact surfaces it is usual in modern heavy current switches not to allow the actual break to be made at them, but on a pair of carbon blocks in parallel with the main contacts. In the breaker described these blocks are above the upper main contacts on strong springs, so set that the carbons are held in contact until the metal surfaces are separated. The whole current is thus transferred without sparking to the carbon blocks, which separate a fraction of a second later with probably a big spark or flash. The carbon blocks can be readily renewed at a trifling cost if damaged. The linkages are also so arranged that the upper contact of the bridge-piece *a* opens before the lower, at which, therefore, there is no sparking.

A very interesting accessory is the iron ear, which can be seen in the photograph, surrounding the sides of each carbon block on both the fixed and the moving contacts. These ears on the two sides set up a magnetic field across the widening gap as the breaker opens, and this field acts as a magnetic blow-out. The field drives the current towards the edges of the carbons, and the space between the carbons is cleared of the arc, which then rises naturally from the top of the carbons, where it is smoothly broken by the natural draught and the repulsion due to its own magnetic field.

Operation of Circuit-breakers.—The occasions upon which a circuit breaker should operate are very similar to those described elsewhere in connection with special applications. They may be summarised as :-

(*a*) When there is an excessive current in the mains.

(*b*) When the working voltage sinks to a low value or nil.

(*c*) When the flow of current, or energy, is reversed.

In some cases it may be desirable or even necessary that the breaker should open instantaneously or practically so, whilst in others it may be desirable to allow a brief interval for normal conditions to re-establish themselves, and time-limit devices are introduced into some part of the apparatus which controls the operation of the tripping coil.

The electrical arrangements for operating the tripping coil depend somewhat upon whether the switch itself, as a switch, is hand or otherwise operated. They also depend upon the voltage—low, medium, or high—of the circuits upon which the circuit-breakers are placed.

For hand-operated circuit breakers on low-voltage circuits the coil may be a heavy current coil in series with the circuit-breaker, and carrying the whole, or a definite fraction, of the current passing through the switch. From what is said elsewhere, it will be understood that the armature of an electro-magnet, or the plunger of a solenoid, set in motion by the current in the coil, knocks out of the way a catch or trigger which releases the mechanical energy in a coiled spring, or else allows the force of gravity to act, in either case forcibly drawing the contact surfaces of the switch out of contact as soon as the current in the tripping coil has reached a certain prearranged value. When carrying the whole current the coil is mounted on the circuit-breaker and connected up between one of the terminals and one of the fixed contacts of the breaker.

In motor or solenoid operated circuit-breakers on high-voltage circuits the trip coil is usually placed, as shown in Fig. 561, in the low-voltage operating circuits, and has its current controlled by a relay or relays whose "live" coils are either in the main circuit or in the secondary circuits of series instrument transformers whose primaries are in the main circuits. Some such transformers have been described on pages 967 to 972, and their use referred to in other places in the book. The relays used in connection with the tripping coils of circuit-breakers are interesting, and in what follows are classified for convenience according to the particular adverse contingency, as specified above, under which they are designed to operate.

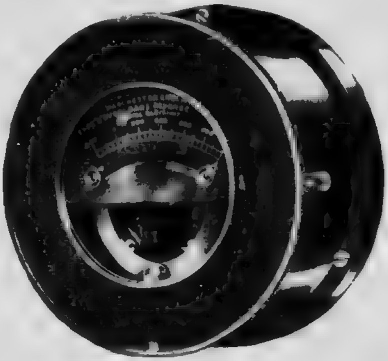


Fig 1,384.—Westinghouse Overload and Reverse Current Relay.

Overload Relays.—In high-voltage circuits, with remote control switches, the trip coil is necessarily operated by a relay, and this is often found desirable, as explained, in low-voltage circuits also. These relays are different for C.C. and A.C. circuits, and the designs are numerous.

C.C. Relays.—A standard type of continuous-current relay is shown in Fig. 1,384, and some of the details are more clearly shown diagrammatically in Fig. 1,385. This relay is designed by the British Westinghouse Company to control circuit-breakers fitted with shunt trip coils, the contacts in the "local" circuit being intended to close a circuit in which the current shall not exceed 2 amperes at 125 volts. The relay, of which Fig. 1,384 is an external view, is essentially a moving-coil galvanometer with the pointer replaced by an arm carrying a contact maker, the position of this arm depending upon the magnitude and direction of the current, so that when the current in the "line" circuit exceeds a specified amount the arm closes the contact of the "local" circuit, in which the tripping coil of the circuit-breaker is placed.

In the diagram of Fig. 1,385, M is the permanent magnet of the moving coil galvanometer, and *p p* are the pole pieces; *c* is the moving coil itself connected to the main "line" terminals T_1 and T_2 by the usual methods, which are not shown in the diagram. The "local" circuit of the relay is brought to the terminals t_1 and t_2, the contacts to be closed by the moving coil being c_1 and c_2, of which c_1 is carried by the moving coil, and is connected to t_1 by a flexible ligament *l*. The other contact c_2 is carried by an adjustable contact arm A, the position of which alters the contact distance between c_1 and c_2, which has to be bridged by the motion of the moving coil; *f* is a flexible connection between c_2 and the fixed terminal t_2, and S S is a scale, seen in Fig. 1,380, showing the currents at which the relay is set to operate.

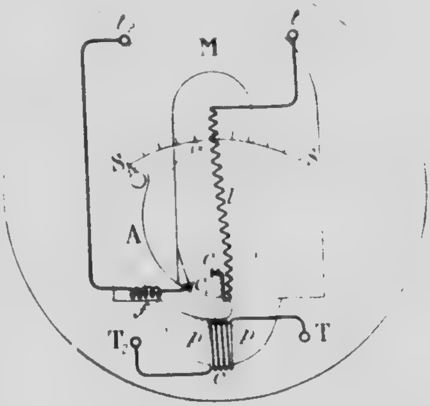


Fig. 1,385. Diagram of the Westinghouse D.C. Relay

A.C. Relays.—A simple form of A.C. overload relay, as manufactured by Messrs. Ferranti, is shown with its protecting cover removed in Fig. 1,386; it is designed to be fixed on a switchboard, from which it projects only 6¾ inches. In the lower part of the instrument there is an electro-magnet, which is energised by current from the circuit to be protected. This electro-magnet has an armature partially balanced by a sliding weight, and when drawn upwards by magnetic action it lifts the moving contacts of a contactor, which can be seen in the upper part of the figure. The movable contacts are raised until they engage with two fixed contacts, thus either closing or opening the trip-coil circuit as may be necessary according to the arrangement of the switch mechanism. The armature is raised against the action of a spring which ensures a good "pull off"

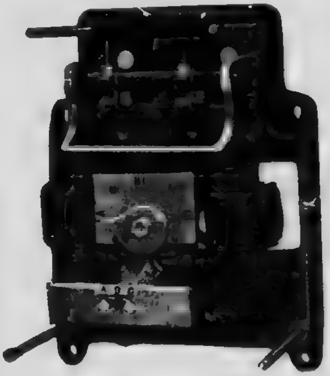


Fig. 1,386.—Ferranti A.C. Overload Relay.

when the electro-magnet loses its current. The electro-magnet is energise by either two or three coils. For single-pole working there are tw coils in series; for double-pole working there are two coils in differen phases, and for triple-pole working there are three coils, each in different phase. There are three coarse and three fine adjustments fo sensitiveness, allowing an over-all adjustment of from 60 to 400 per cent of normal full load. The coarse adjustment consists of altering, by mean of a cam which has three positions, the air gap between the armature and the core of the electro-magnet. The fine adjustment is obtained by altering the position of the sliding weight.

Inverse Time-limit Relays.—Experience has shown that only in exceptional cases is it desirable that the action of a protective device should be instantaneous. Oftentimes the abnormal disturbance guarded against is only of short duration, and sometimes even a fault may be burnt out fairly harmlessly in a few seconds if the supply of electric energy be maintained. It is therefore desirable that the time taken by the protective device to operate should depend upon the seriousness and dangerous character of the fault. This condition is to some extent satisfied by an ordinary fuse, which will blow at once on a very heavy overload, but will take some time to break circuit if the current be only a little above the limit. In other words, the greater the danger the shorter is the time of action; hence the term "inverse time" as applied to apparatus having this property.

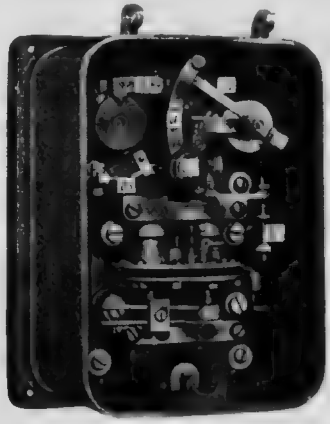


Fig. 1,387.—Ferranti Time-limit c.c. Relay.

Special fuses constructed so as to make the time element more definite have been described above (*see* Fig. 1,367, page 1326), and by using a suitable fuse of this type connected in parallel with the A.C. relay described on page 1337, Fig. 1,386, this relay can be used as a time-limit overload A.C. relay.

Time-limit relays are, however, often constructed with definite mechanical adjustments, such that the minimum current for which the relay is set to act will cause the relay to operate in a definite time, which will become shorter and shorter as this minimum current is exceeded.

Such a relay, designed for *c.c. circuits* as made by Messrs. Ferranti, is shown in Fig. 1,387 with its front cover removed. The operating part of the relay is a small mercury motor similar to that used in the well-known Ferranti C.C. meters and fully described in the section on Electric Meters.

The motor, instead of driving a counting train, carries on the upper part of its spindle a small drum, which, by means of a silk cord passing round a grooved disc, moves an arm, seen at c_1, carrying a movable carbon contact, until it comes into contact with the fixed carbon opposite to it. The movable contact is hidden by the segmental fixed arc *a*, to which the fixed contact is attached behind the nut at c_2. The far end of the silk cord has a weight *a* suspended from it, which it lifts when the motor rotates. The position of the fixed contact on the segment *a* can be adjusted, thus altering the time required for the motor to close the gap; also if the weight *a* to be lifted be increased, a bigger current will have to flow through the motor before it can be lifted. Thus both the actual time-lag and the minimum current required to work the relay can readily be altered. When once set the connection between the current on the main circuit and the time required for the relay to close the trip circuit is as shown in Fig. 1,388, in which curves A, B, and C are for maximum time-lags of 15, 10, and 5 seconds respectively and for a minimum current of 750 amperes, whilst the dotted curves *a*, *b*, and *c* are for similar maximum time-lags, but for a minimum current of 800 amperes. As is the case in the meter, only comparatively small currents, up to 20 amperes, are allowed to pass through the motor. For larger main currents up to 10,000 amperes standard shunts are provided, which, when inserted in the mains, supply the motor with the necessary operating current with a drop in the mains of 0·075 volt

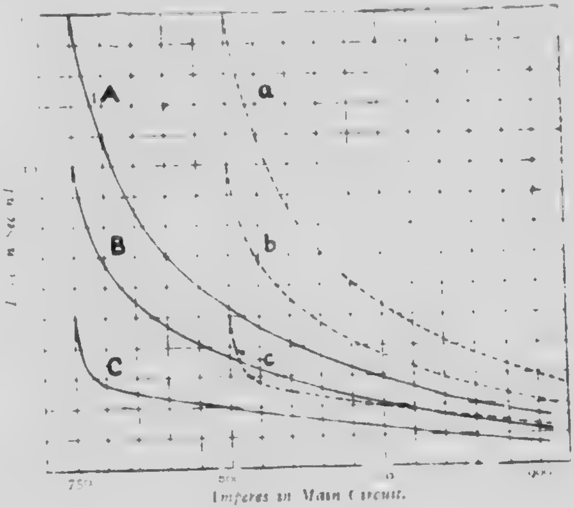


Fig. 1,388.—Time required to close Relay Circuit with different Currents.

Fig 1,389.—Westinghouse Time-limit Relay.

up to 1,500 amperes and with a drop of 0·05 volt for heavier currents.

A favourite device, used to delay the action of a relay in closing its "local" circuit contacts, is that of the dash-pot, examples of which have occurred elsewhere in this book. Its application for a time-limit relay is shown in Fig. 1,389, which is from a photograph of the standard time-limit relay designed and manufactured by the British Westinghouse Company. The dash-pot is visible on the left-hand side of the figure, the centre of which is occupied by the solenoid electro-magnet which closes the "local" contacts when energised by the current in its "line" circuit. The plunger of the solenoid is connected by linkages with the piston in the dash-pot, and the distance through which the plunger must move to close the contacts can be set by moving and then clamping the index seen in front. The scale gives the time interval within which the contacts will be closed with the minimum operating current in the solenoid. If during this interval the overload disappears the contacts will not close and the relay will re-set itself.

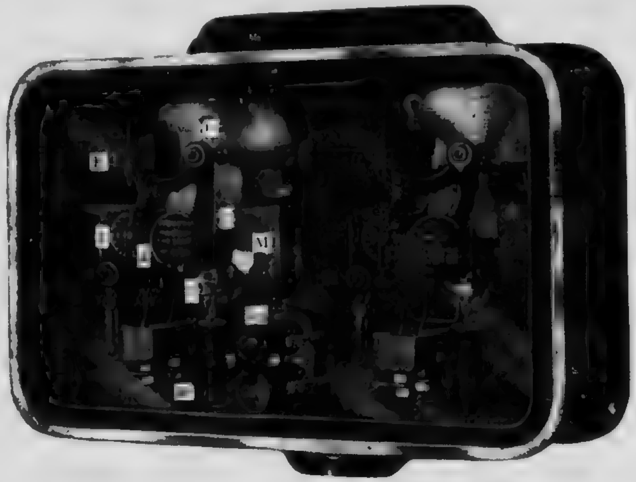


Fig. 1,390.—Ferranti Overload Time-limit A.C. Relay.

An overload time-limit relay for *A.C. circuits* as made by Messrs. Ferranti, in which small induction motors are used, is shown in Fig. 1,390. The relay shown is a double-pole relay, with a separate and distinct mechanism for each pole, because complete protection with A.C. time-limit relays can only be ensured by a separate relay being used for each phase. This relay is adapted to open (not to close) the trip-coil circuit of the main switch. An electro-magnet E, energised by current from the circuit to be protected, has an air gap in which a vertical copper disc D, mounted on a horizontal spindle, can rotate. The alternating magnetic flux produces eddy currents in the disc, and by suitably shading the poles as in some types of meters (*see infra*), part of the flux is caused to lag and by its action on the eddy currents a driving torque is exerted on the disc, the motion of which is retarded by the usual permanent damping magnet M. A silk cord c is wound round a drum on the spindle of the copper disc, and passing under a jockey pulley p and another drum d, has its other end attached to a winged handle moving over a graduated scale. By altering the position of this handle the height of the jockey pulley can be adjusted. The jockey pulley carries a weight w. When the disc D rotates it lifts w, which near the top of its travel engages with a lever which actuates the relay contacts.

The current passing through the magnet determines the torque on the disc D, which cannot move until this torque is sufficient to lift w, thus fixing the minimum current, below which nothing occurs. By altering the weight to be lifted this minimum current can be varied, and by adjusting the free length of the silk cord, by moving the winged handle over the scale s, the time during which the weight is moving upwards before it strikes the lever can be varied. Three weights are provided for each element, the two w_2 not in use being held in special clips.

The standard load settings by altering the weights are 125, 150, and 200 per cent. of full normal load, and the standard time settings at 0, 5, and 10 on the scale s correspond to maximum time-lags of 8, 18, and 25 seconds respectively. The curves connecting time-lag and overload current are similar to but not identical with curves already given (Fig. 1,388) for other relays.

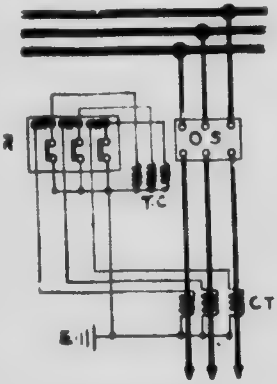


Fig. 1,391. Connections of Relay (Fig. 1,390) to Open Circuit

The connections for a relay which opens instead of closing a circuit are shown in Fig. 1,391, in which it will be seen that the trip coils T C of the oil switch O S are short-circuited by the contacts being closed in the relay R, in which case they do not receive current from the current transformers C T until these contacts are opened, when they are placed in series with the working coils of the relay.

No-volt Relays.—In some systems of protection it is arranged for the protective gear to operate when the voltage falls below a predetermined minimum, and relays have been designed to operate accordingly.

The Ferranti relay described on page 1337 (Fig. 1,386) is modified for this purpose by substituting a solenoid and plunger for the electromagnet and armature. The solenoid being supplied, either direct or through a potential transformer, with a current varying with the voltage, the plunger is held up by the magnetic action until the voltage falls to approximately 40 to 60 per cent. of normal value, when it is released, and in falling lifts the movable contacts. Standard no-volt coils are supplied up to 600 volts.

Reverse Power.—In a complicated system of electric power supply it is obviously essential that the generators on the system should run only as generators and not as motors driven by electric power flowing in the opposite direction. When any sources of E.M.F., such as secondary batteries, etc. are at the consumers' ends of the system, it may happen that by a special combination of circumstances—including, it may be, the failure of certain automatic apparatus—the E.M.F.s so present may either directly or indirectly exceed the driving E.M.F.s, and power may thus—for a time, at any rate—flow back to the generating station

This contingency must obviously be safeguarded, and we have elsewhere described one or two methods of doing this in special cases (*see* pages 1284 and 1336).

Dealing with the matter a little more generally but quite briefly, it may first be noted that in C.C. circuits the reverse flow can only be effected by a reversal of current, whereas in A.C. circuits a change of the phase angle between voltage and current may have the same effect. If, for instance, in a single-phase circuit the angle, whether leading or lagging, between the voltage and the current exceeds 90°, the power factor (cos φ) becomes —' the physical interpretation of which is that the direction of the flow of power in the circuit is reversed. The reversal of current in a C.C. circuit is, in fact, however, only a special instance of the more general A.C. case.

Reverse C.C. Power.—For low-voltage C.C. circuits it is not difficult to design polarised circuit-breakers which shall open the circuit immediately a current flows in a direction contrary to that required. The apparatus described at page 1332 is such a polarised circuit-breaker. Other methods will readily suggest themselves, but it must be borne in mind that the current may, and in the usual case will, reverse without the mains altering their relative polarity; in other words the +" main remains +'. It may, however, in a given case be more convenient to work through a suitable relay rather than by means of the whole, or a fraction, of the current passing through the circuit-breaker.

A *reverse current relay* for C.C. circuits is made by Messrs. Ferranti, as an adjunct to the C.C. inverse time-limit relay described on page 1338 (Fig. 1,387). If the current be reversed the motor runs in the reverse direction, and a second silk cord from its spindle acts against the torsion of a light spring, which is holding apart the contacts at c_3. By setting up the spring the motor can be made to start with different currents, the standard settings being for 15, 25, and 45 per cent. of normal load. The time element can be varied as before by altering the length of the gap at c_3.

The relay shown in Fig. 1,384 can also be modified to act as a reverse continuous-current relay, inasmuch as when the current is reversed the movable arm will be deflected to the left instead of [illegible] right and with a much smaller current in the coils, as is [illegible], the needle closes "local" contacts.

Reverse A.C. Power.—In A.C. circuits reverse relays are usually required to work with small amounts of power with which it is not possible to energise tripping magnets direct from the secondaries of current transformers; relays to open circuit should therefore be used with "no-volt" trip coils.

These relays are similar in the electric and magnetic details of their design to the *induction* wattmeters and energy meters described elsewhere. For instance, a pattern made by Messrs. Ferranti is based upon the same principles as their induction wattmeter described later, the spring controlling the motor disc being replaced by a small weight hanging from one end of a silk cord, the other end of which is attached to a small drum on the rotor spindle. Rotation for forward power is prevented by a stop but if the disc tends to rotate in the opposite direction owing to the reversal of the power, it lifts the suspended weight and actuates a contactor, thus opening or closing the trip-coil circuit. The relay is set to operate when the reverse power attains a predetermined magnitude, which must not be less than 10 per cent. of the normal load with a minimum voltage of 20 per cent. of the normal. The series windings of the relay are connected to a current transformer and the shunt windings to a potential transformer if the supply voltage exceeds 300 unless impedance coils are used, in which case the instrument can be connected direct on circuits of voltages not exceeding 650. On three-phase circuits the relays should be connected between outers and neutrals, and if an artificial neutral point is necessary it can be obtained by connecting three relays in star, or if fewer than three relays are employed by using neutral point choking coils. Relays on several circuits can have their shunt windings supplied by one potential transformer of proper capacity if the circuits are all fed from the same supply.

Relays specially designed for balanced systems of protection are described in the next section.

III.—BALANCED SYSTEMS OF PROTECTION

The devices hitherto referred to in this chapter should operate when a fault occurs on the system, and in cases of temporary overload or of sudden surges, but in so operating they may disconnect large sections of the system which are in good running condition. In extensive and complicated systems it is advantageous to have also available what have been called "discriminative" protective devices, absolutely unaffected by faults external to the section on which they are placed, and designed to disconnect automatically faulty apparatus only, leaving in circuit the outlying healthy apparatus.

The best-known system of this type, specially worked out for A.C. circuits, is the Merz-Price protective system, extensively used by the Newcastle and Durham Power Companies, and the Merz-Hunter split-conductor system developed from it.

Merz-Price System.—The simplest application of this system is to the protection of a *single feeder*, such as is shown in Fig. 1,392.* The principle employed is that if the feeder be perfectly insulated the current which flows out at B will be the same as the current which flows in at A; but if a fault develops between the two ends of the cable, these currents will differ by the amount of the leakage current or currents. Oil switches S_1 and S_2 are installed with their trip coils C_1 and C_2 at each end of the line. In the diagram the trip coils are operated by the batteries b_1 and b_2 if and when their circuits are closed by the local circuit contacts of the relays R_1 and R_2. At each end of the feeder there is a current transformer, the two transformers T_1 and T_2 being exactly similar. The secondaries of these transformers are connected as shown by the pilot wires, with the connections of one of them reversed, so that if the entrant and emergent currents in the feeder are the same no current will flow in this secondary circuit, in which are the "line" coils of the relays R_1 and R_2 also in series. If, however, there be a leak in the feeder the entrant and emergent currents will differ, and the balance in the secondary coils will be upset, currents will flow in the "pilot" wires, the relays will act and the trip coils operate, the result being that both oil-switches will open, thus cutting the feeder out of the system at both ends.

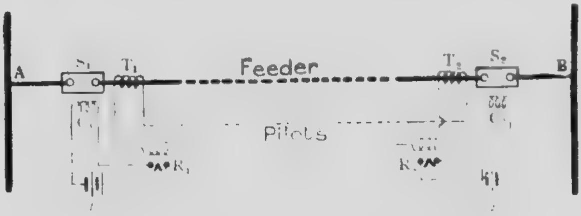


Fig. 1,392.—Connections for Merz-Price Balanced Voltage System of Protection of Feeders.

The application of this system to *three-phase feeders* is shown diagrammatically in Figs. 1,393 and 1,394, for which the author is indebted to Messrs. Reyrolle and Co., who have made a speciality of these methods of protection. In both figures current transformers, T_1 and T_2, are placed upon each main conductor of the three-phase feeder, but in Fig. 1,393 the secondaries of these transformers are connected in star, whilst in Fig. 1,394 they are connected in series, proper attention being paid to polarity. In Fig. 1,393 the secondaries on the two ends of the same conductor are connected, by pilot wires, in series between the star points, and in each of the connecting wires there are the line circuits of two relays *r*, one at each end of the corresponding pilot wire. This is all as [illegible] except that the return circuit for each conductor is supplied by [illegible] the neutral points at the two ends. In Fig. 1,394 on the other hand, there is only one circuit through the six secondaries in series, and in this circuit, which is insulated throughout, there is the [illegible] circuit of one relay at each end.

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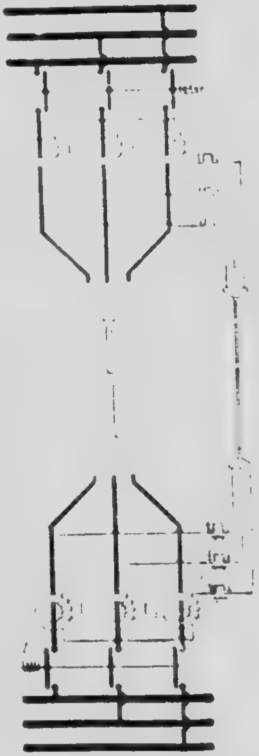
* These and some of the subsequent figures are taken from papers read before the *Institution of Electrical Engineers*.



[illegible]

In both diagrams it is assumed that the secondaries of the transformers are so connected that when the currents in the main conductors are balanced the E.M.F.s at the two ends of the pilot wires are balanced, and no current flows in these wires. In this case the relays are quiescent and nothing happens. If, however, through a fault on one of the feeders the currents in any one of the three conductors are different at the two ends of the conductor, or if there is a simultaneous fault on all three conductors, the E.M.F. balance will be destroyed, currents will flow in the pilot wires and one or more of the relays at each end will operate, currents will flow in the local circuits of the relays, and the tripping coils t_1 and t_2 in [illegible] circuits will [illegible] and open the main circuits [illegible] tripping-coil circuits are [illegible]. One difference between the two [illegible] Fig. 1,393 requires [illegible] wires, whereas Fig. 1,394 [illegible] and two pilot wires.

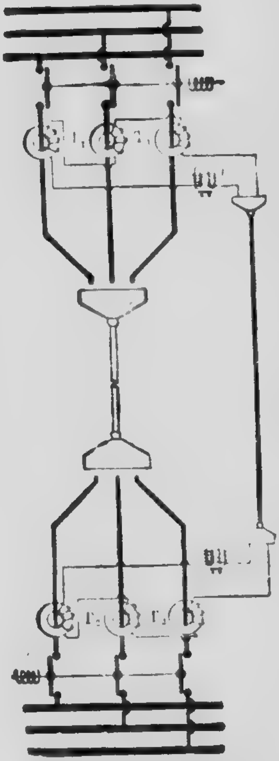


Fig. 1,393. Balanced [illegible] Protection for Three-phase Feeders (Transformers [illegible] connected)

It will be noticed that [illegible] advantage attached to [illegible] two or more pilot wires [illegible] be run from end to end of the feeder [illegible] feeder, whether they be embodied in the [illegible] or, for overhead lines, be run on separate insulators on the same poles as the main feeder. The voltage on these pilot wires is obviously quite low.

Transformers.—Another simple application, which does not involve the last-named disadvantage, is to the protection of transformers as shown in Fig. 1,305 for a single-phase transformer. Series transformers T_1 and T_2 are inserted in the primary and secondary circuits, one in each circuit of the transformer T, to be protected. The windings of the transformers T_1 and T_2 are such as to allow for the normal ratio of the currents in the transformer T, and their secondaries are so connected that their E.M.F.s are in series. A current therefore circulates in the secondary circuit through the connecting wires, which are, of course, quite short. The trip coils C_1 and C_2 of the oil-switches or circuit-breakers in the main circuits of T are connected in parallel to two equipotential points *a* and *b* on the secondary circuit of T_1 and T_2, and receives no current whilst things are normal. Should, however, the ratio of the primary and secondary currents of T be changed the balance will be upset, and *a* and *b* will no longer be at the same potential. Currents will then flow through the trip coils, and if sufficiently large will open both the switches or circuit breakers, cutting the coils of T quite out of circuit.

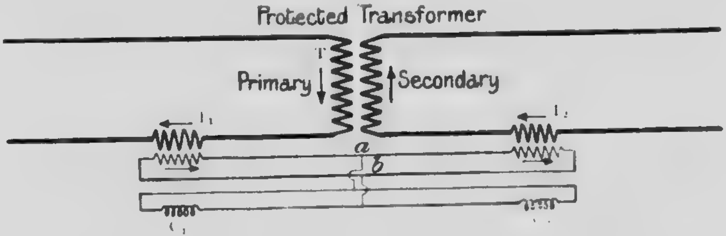


Fig. 1,305.—Merz-Price Circulating Current System applied to Transformers.

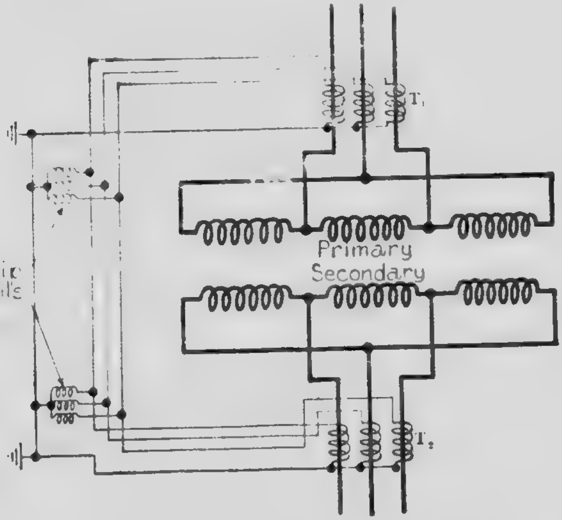
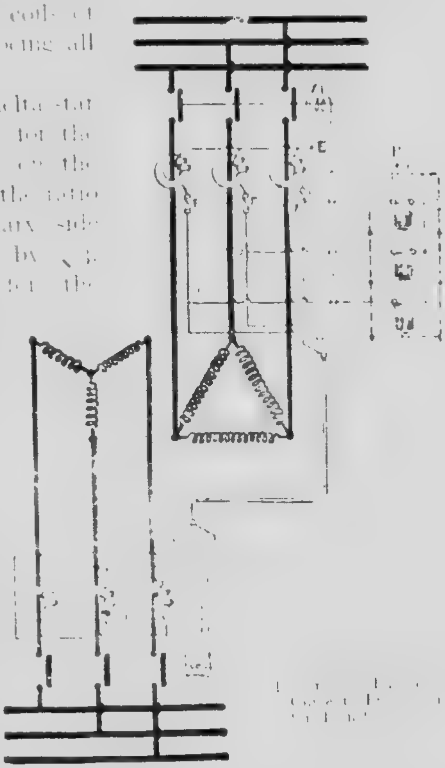


Fig. 1,306.—Application to a Three-phase Transformer.

The application to a delta-delta connected three-phase transformer is shown in Fig. 1,306, which needs no further explanation except to point out that the secondaries of the series transformers T_1 and T_2 are star-connected, as also are the trip coils of the switches, the four star points being all connected to earth.

If the main transformer be delta-star connected, allowance must be made for the phase relationship (see page [illegible]45) on the two sides of the transformer, and the ratio of transformation on the secondary side must be increased by multiplying by √3. Allowance must also be made for the permanent out-of-balance current due to the no-load exciting current, and if there be tappings on the main transformer, similar tappings must be provided on the series transformer.

Details of the [illegible] of delta-star [illegible] [illegible] are given in Fig. 1,397, in which the tripping coils are operated by relays and not direct from the secondaries of the current transformers as in Figs. 1,305 and 1,306. The diagrams of the circuits of the secondaries and the line circuits of the transformers, without the local circuit, are shown in Fig. 1,398. The secondaries of the current transformers on the delta-connected side of the main transformer are connected in star, whilst the similar secondaries on the star-connected side are connected in delta. In this way the phase-differences of the currents in the main conductors are taken into account. The two tripping coils are brought into parallel across the battery B, by the closing of any one or more of the local contacts of the relays. The line circuits of the relays are bridged in star across the connecting wires of the secondaries on the two sides, and it is obvious that to carry out the general principle indicated for the circulating current method of Fig. 1,305, the actual connections must be carefully worked out. A fuse *f* is joined across the line terminals of each relay, and these fuses practically short-circuit the



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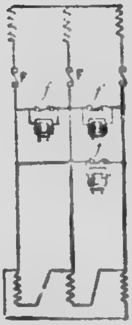


Fig. 1,398.—Diagram of the Line Circuits of the Relays.

three points *a* in the connecting wires. If any two of these points cea to be at the same potential a current will pa through the fuse *f* until the fuse blows, and tl relay is brought into action.

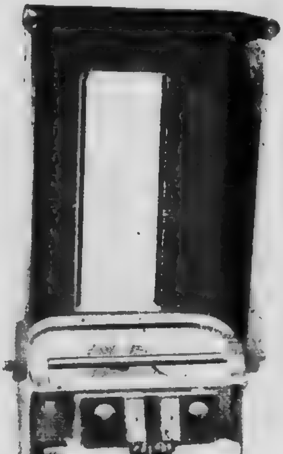


Fig. 1.399.—Single-phase Merz-Price Relay ("Local" Circuit Closed).

The same principles can be, and are, employe to protect the windings of an A.C. generator fro any fault occurring in the machine itself, an other applications have been made.

The Merz-Price relay designed for use with the systems and manufactured by Messrs. Reyroll and Co. is shown in Fig. 1.399. It consists of substantial two-limb electro-magnet with a ver light armature with a small air-gap to ensu rapidity of action. When the armature is raise the battery circuit is made through the trippin coil and simultaneously a heavy contact weigh is released and in falling closes a parallel contact ensuring that the local circuit of the relay shal remain closed. This weight W, in Fig. 1.399, is shown in its "down" position connecting together the two flexible contact springs.

For three-phase working three of the single-phase relays shown in Fig. 1.399 are assembled in the same case as shown in Fig. 1.400, in which the heavy contact weights appear in the raised position in which, when the relays have operated, they can be replaced by the push spindles without opening the case.

Merz-Hunter System.—This system known as the "split-conductor" system, is specially suitable for the selective protection of main cables, whether used as ring mains, interconnectors, duplicate feeders, or otherwise in a distribution system. Its special advantage is that it is very sensi-

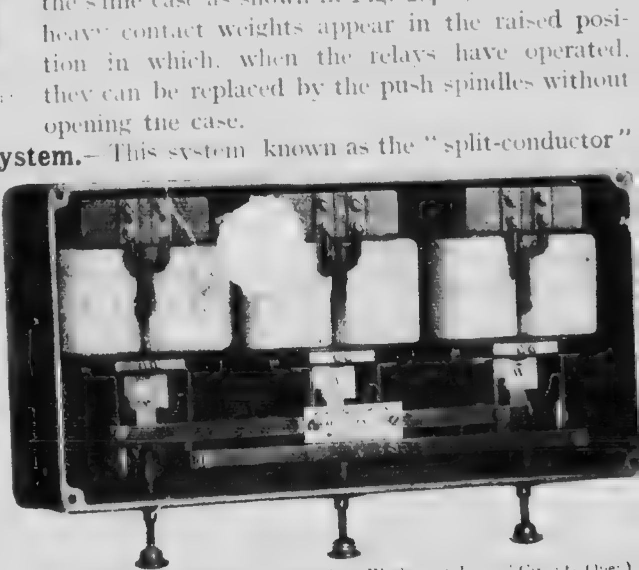


Fig. 1.400.—Merz-Price Relays for Three-phase Working ("Local" Circuits Open).

tive, and will operate instantaneously with a [illegible] load current. On the other hand it [illegible] special construction, or, if applied to overhead wires, [illegible] conductors.

The special feature of the system is the [illegible] of each conductor into two parallel conductors, which need only be lightly insulated from each other, as shown in Fig. 1,401, which is a diagrammatic section of a three-core split-conductor lead-covered and armoured cable, differing only from similar cables illustrated in Chapter XI. by the fact that each core consists of two oval concentric stranded conductors which at the ends are electrically connected in parallel. The conductors are of equal cross-section, and in normal working there is no P.D. between them. The oval shape is adopted as giving the best distribution of potential strain in the dielectric. The cost of such cables is said only to be slightly in excess of the standard patterns.

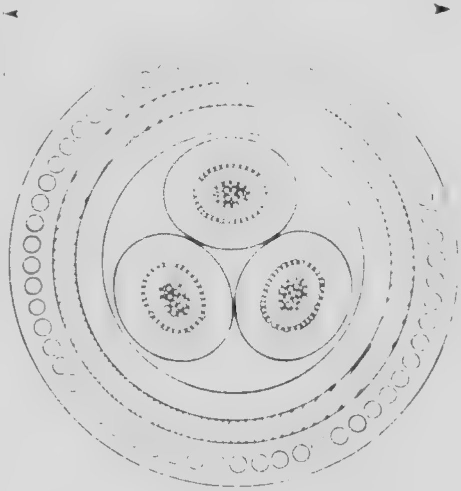


Fig. 1,401.—A [illegible] Split [illegible]

The method of protecting one of the cores of the cable is shown in Figs. 1,402 and 1,403, the first of which shows a core in sound condition, and the second one in which a leakage fault has developed near one end. At each end of the cable the two halves of the split conductor are connected through the primary windings of special current transformers, represented diagrammatically by T_1 and T_2 in each figure. The middle of each winding is connected through an oil switch to the usual switchgear, etc., the energy flowing from the generator end G to the load end W. The core *c* of either transformer T carries the secondary winding which is closed through the line circuit of the relay R controlling the oil-switch. When, as in Fig. 1,402, the conditions are normal and the two halves of the split conductor are carrying equal currents, the cores c_1 and c_2 of the

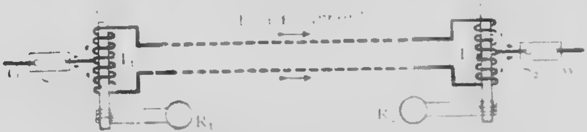


Fig. 1,402.—The Split Conductor System. Fig. 1,403.

transformers are not magnetised, nor do they become magnetised for overloads or any fault the current from which will divide equally between the two halves o the conductor.

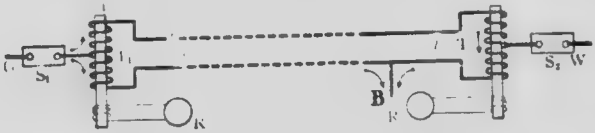


Fig. 1.403.—Protected Faulty Split Conductor.

When, however, a fault develops as at B in Fig. 1.40 it is necessarily on the outer conductor *o o*, and the inflowing current at G is no longer equally divided, so that the balance of the magnetising circuits on T_1 and T_2 is destroyed. In T_1 the current, passing to the outer conductor *o o*, is increased, and its magnetic effect overpowers that of the current in the inner conductor *i i*. In T_2, if the fault be near the end W, as in Fig. 1.403, a current will flow from T_2 towards the fault, entirely reversing the magnetic effect of the lower half of the primary coil. In both transformers, therefore, currents are set up in the secondary coil circuits, the oil-switches are opened and the faulty cable disconnected.

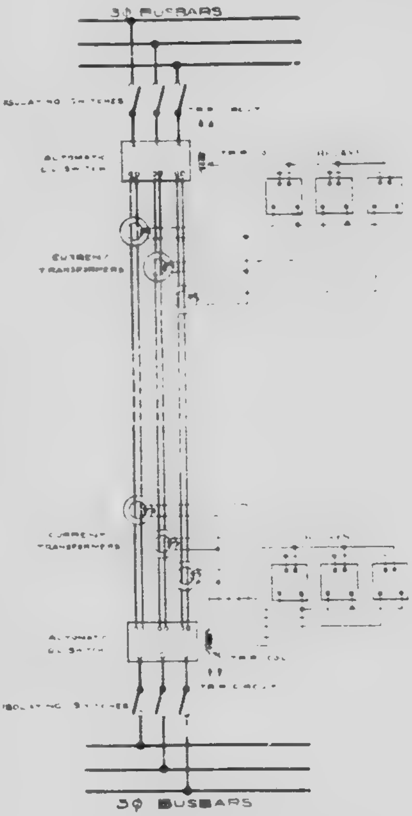


Fig. 1.404.—Three-phase Feeders with Split-conductor Protection.

It has been assumed in the above that the fault which causes the relay to operate occurs on one half-conductor only, but even if faults occurred simultaneously on the two halves it is practically impossible for the impedance of the two faults, and therefore the two fault currents, to be similar. In practice the oil-switch is so constructed that, when it opens the two halves of the split-conductor are separated from each other as well as from the busbars. If, therefore, the oil-switch nearer to the fault opens before the more distant one, it leaves the fault on one half-conductor only, and this secures the immediate operation of the relay at the distant end.

A three-phase split-conductor cable, such as is depicted in Fig. 1.401, requires a current transformer with double wound primary at each end of each split conductor in the cable. The complete system of protection for such a cable is shown diagramatically in Fig. 1,404. After the above explanation this diagram will be self-explanatory, but attention may be called to the fact that the secondaries of the three current transformers at each end of the cable are star-connected, as also are the "line" coils of the three relays, and that the two neutral points at each end are joined together. The "local" contacts of the relays are bridged across the leads of the trip-coil circuit, so that if any one of the relays acts, that circuit is closed, and the oil-switch is opened.

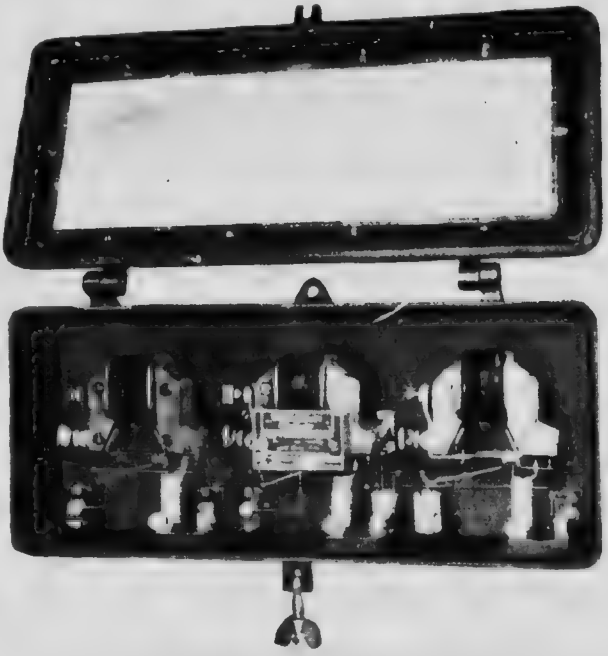


Fig. 1,405.—British Westinghouse Three-pole Relay for Split-conductor System.

A three-pole relay made by the British Westinghouse Company for use on such a split-conductor system as is shown in Fig. 1,404 is illustrated in Fig. 1,405, in which the three separate relays are mounted in one box. The details of the magnetic and electric circuits of the electro-magnets can be readily made out. The armatures are very light, and shaped so as to present a large surface to the pole faces; the mounting of each is pivoted at the side of the left-hand pole, and the air-gap can be adjusted to a nicety by the screw s. It is claimed that the action is so rapid that when it is applied to an overhead system, should one of the two conductors break the oil-switches at each end of the line will be opened, and be made "dead" before the ends of the broken conductor can reach the ground.

Core Balancing System.—One other neat balancing device may be mentioned in conclusion. The principle is shown diagrammatically for a simple case in Fig. 1,406. A star-connected three-phase alternator G with its neutral point earthed, is connected to the mains through an oil-switch s. So long as the insulation of the transmission and utilisation systems is perfect, the current which at any instant is passing down the conductor of one phase must return through the other conductors; or, in other words, the sum of the three currents must be zero. If, therefore, a secondary-wound laminated iron core be placed round the three-core cable, this iron will not be magnetised and no current will be set up on the winding of the coil surrounding it, the core and coil being similar to that illustrated in Fig. 901. Should there, however, be a leak on one of the phases, part of the current down that phase will return to the generator G by earth, and the sum of the currents on the three conductors will no longer be zero. The core will therefore be magnetised, and currents will be set up in the secondary, which will operate the relay, close the battery circuit and open the oil-switch.

The reader who wishes to follow up other applications should consult an interesting article by Mr. E. B. Wedmore in the *Journal of the Institution of Electrical Engineers*, Vol. LIII. (1915), pages 157 *et seq.*

More recently Messrs. Glover & Co. have worked out a balanced protective system in connection with their "test-sheath" cable (see page 1158). Principles similar to those just described are applied, the test sheath being used to indicate through relays when the main currents are not balanced. A number of incipient and other faults can thus be readily detected.

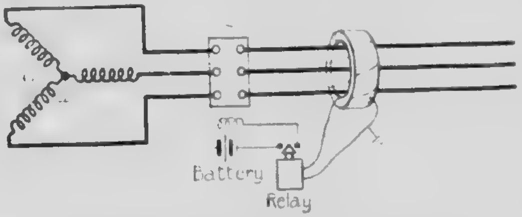


Fig. 904.—Core Balancing System of Protection.

Balanced Systems, C.C. Working.—It is obvious that systems similar to the foregoing can be worked out for c.c. circuits, and, as a matter of fact, this has been done with success. Considerations of space make it impossible for us to give the details of the solutions, but any reader who is interested will find valuable information in an article by Messrs. Rosebourne and Couse in *The Electrician*, Vol. LXXVII., page 189 (1916).

We cannot better close this section than by giving in Plate XV., for which the author is indebted to Messrs. Reyrolle and Co., a diagrammatic lay-out of a large power transmission and distribution scheme with the various protective devices indicated in the generating station, the substations and on the consumer's premises. The system is three-phase, but only a single line is used to indicate the three conductors, except in one or two special positions, which can easily be identified.

Throughout the diagram the small circles drawn round the conductors indicate some system of protection. These systems consist of (i.) simple instantaneous overload release devices marked O; (ii.) time limit overload protective devices, marked T; (iii.) ordinary balanced protective devices

To face page 1352

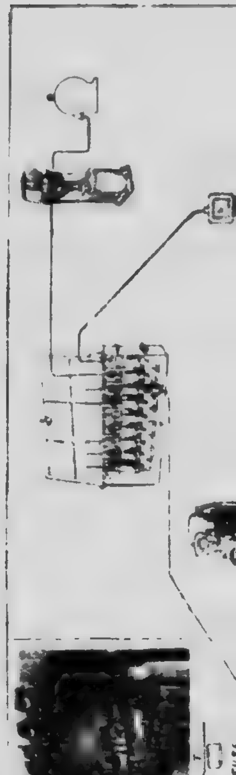
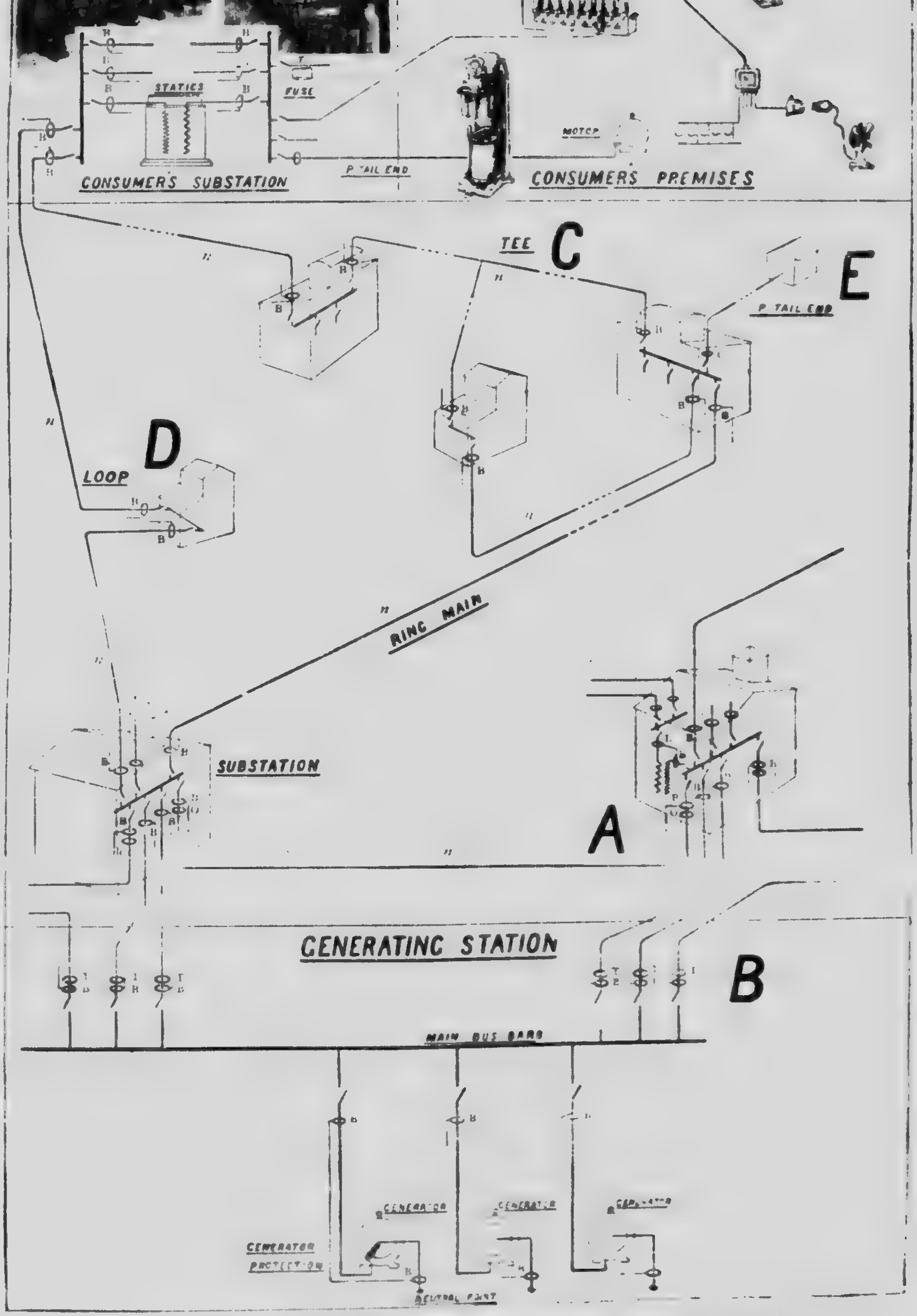


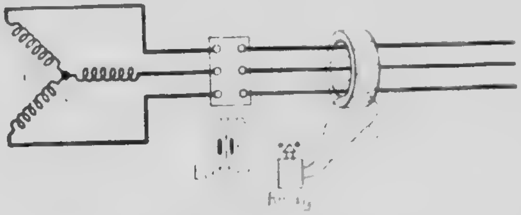
PLATE XV.



Layout of a Feeder for Large Power Transmission and Distribution Scheme [illegible] current which at any instant is passing down the [illegible] must return through the other conductors; or, in other words, the sum of the three currents must be zero. If, therefore, a laminated iron core be placed round the three-core cable, it will not be magnetised and no current will be set up on the winding surrounding it, the core and coil being similar to that illustrated [illegible]. Should there, however, be a leak on one of the phases, the current down that phase will return to the generator G by earth, [illegible] the currents on the three conductors will no longer be [illegible] will therefore be magnetised, and currents will be set up [illegible] which will operate the relay, close the battery circuit and open the oil-switch.

The reader who wishes to follow up other applications should consult an [illegible] article by Mr. E. B. Wedmore in the *Journal of the Institution of Electrical Engineers*, Vol. LIII. (1915), pages 157 *et seq.*

More recently Messrs. Glover & Co. have worked out a balanced protective system in connection with their "test-sheath" cable (see page 1158). Principles similar to those just described are applied, the test sheath being used to indicate through relays when the main currents are not balanced. A number of incipient and other faults can thus be readily detected.



[illegible] System of Protection.

Balanced Systems. C.C. Working.—It is obvious that systems similar to the foregoing can be worked out for C.C. circuits, and, as a matter of fact, this has been done with success. Considerations of space make it impossible for us to give the details of the solutions, but any reader who is interested will find valuable information in an article by Messrs. Rose[illegible] and [illegible] in *The Electrician*, Vol. LXXVII., page 189 (1916).

We cannot better close this section than by giving in Plate XV., to which the author is indebted to Messrs. Reyrolle and Co., a diagrammatic layout of a large power transmission and distribution scheme with the various protective devices indicated in the generating station, the sub-stations and on the consumer's premises. The system is three-phase but only a single line is used to indicate the three conductors, except in one or two special positions, which can easily be identified.

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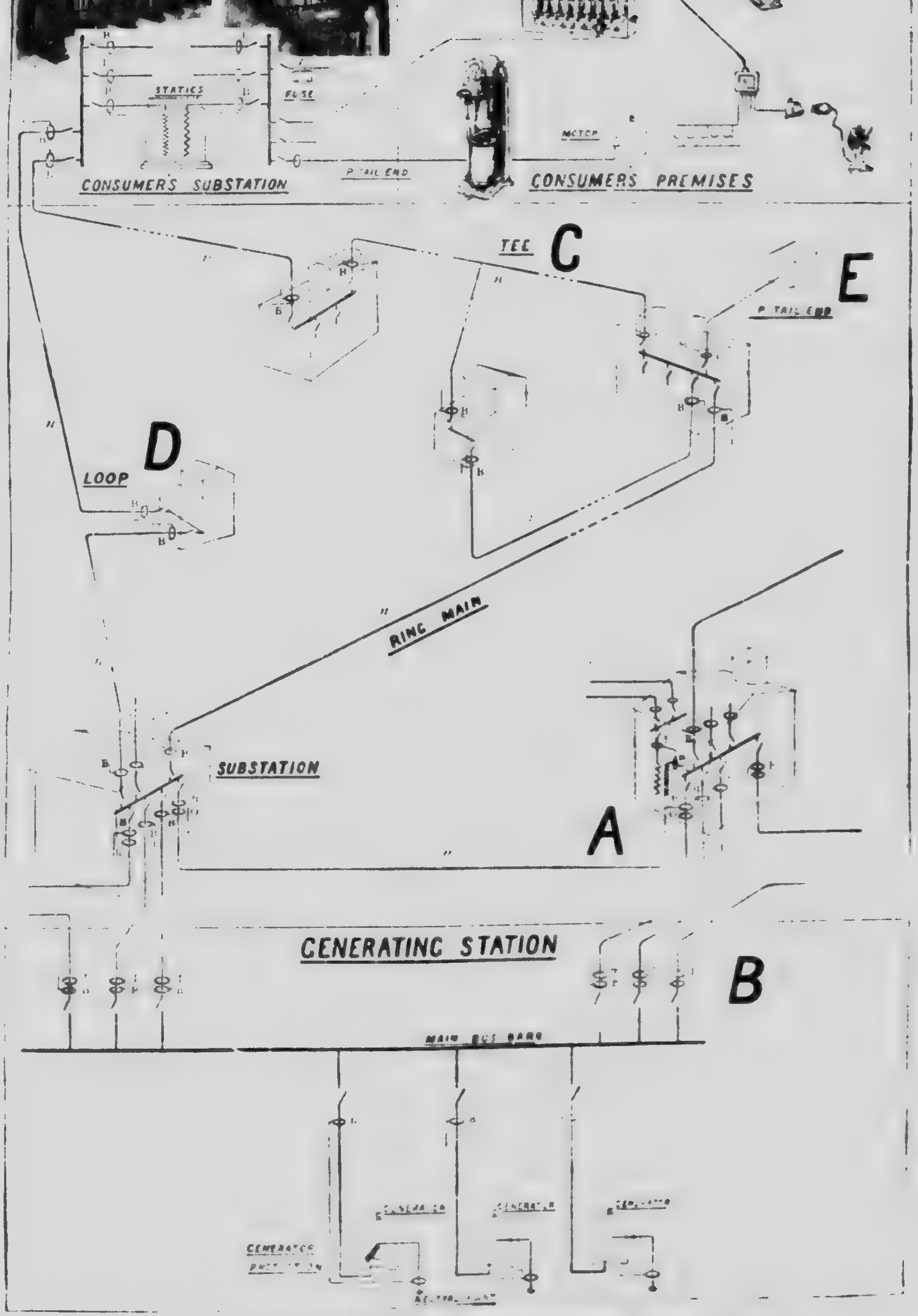
PLATE XV.


STATICS
FUSE
MOTOR
CONSUMER'S SUBSTATION
P TAIL END
CONSUMERS PREMISES
TEE
C
E
P TAIL END
LOOP
D
RING MAIN
SUBSTATION
A
GENERATING STATION
B
MAIN BUS BARS
GENERATOR
GENERATOR
GENERATOR
GENERATOR
NEUTRAL POINT

marked B, and [illegible] protective devices [illegible]. [illegible] part of the diagram there are three generators [illegible] with their armatures star-connected and with the neutral point earthed. The armature windings are protected by [illegible] for one winding on one of the machines. The current from the generators is brought to the main bus-bars upon which [illegible] feeders are shown. Each feeder is fitted with time-limit overload [illegible] protective gear.

These feeders are shown as supplying [illegible] sub-stations, of which there are eight in the diagram, [illegible] protected by balanced protective gear, which, however, has the drawback that the system is left unguarded against certain serious faults. For instance, this protective gear would not provide for the isolation of a sub-station in the event of a short circuit on its bus-bars, and if this happened the whole system might be shut down by the heavy currents set up. To guard against such contingencies, the transmission network is divided into areas which are interconnected, the interconnecting cables *r r r* being protected by instantaneous overload releases O, which will cut out the station before the time-limit overload release in the generating station can act. The [illegible] is another interconnecting device the advantages of which have been referred to elsewhere (*see* page 1202).

At E there is an example of what has been termed "tail-end" connection, in which a simple three-wire cable only is run to a distant such sub-station. Only a core balancing system is used at the near end.

The consumer's low-voltage circuits are only indicated for [illegible] of the sub-stations, and call for no special remark.

IV.—PROTECTION AGAINST SURGES AND [illegible] ATMOSPHERIC ELECTRICITY

The chief cause of trouble external to the circuit (*see* page [illegible]) is the possibility of the overhead line being struck by lightning, and the danger consequently of the electric discharge thus launched upon the circuit finding its way destructively to earth by the conducting paths through the apparatus or machine connected to the line. Causes of trouble more frequent even than the direct striking of the line are the indirect electric surgings due to lightning discharges in the vicinity, and also the slow accumulation of static electric charges on the line which form part of a well-insulated circuit.

These causes of trouble and the lethal danger connected with them were forced on the attention of electrical engineers in the earliest days of the use of overhead conductors for telegraphy, and the devices employed to divert the energy of the consequent discharges from the apparatus and the operators of telegraphic and telephonic circuits are described in the sections devoted to these subjects.

The chief difference between signalling circuits of all kinds and power circuits in the precautions adopted on the circuits themselves, arises from the fact that the latter, unlike the former, have large reserves of power connected to the circuit, and, acting like the trigger of a gun, the lightning discharge, as will appear later, may cause these reserves to act destructively at a point in the circuit at which no such action would otherwise take place.

Fuses and circuit breakers, together with the various auxiliary apparatus designed to make them more effective, as described in the preceding sections, may be regarded as providing fairly good protection against those faults which, from an electrical point of view, develop rather slowly. They may, and do, sometimes fail to act when the danger arises from electrical surging or from a lightning discharge which develops so rapidly that the time which a fuse takes to blow or a circuit-breaker to open is long in comparison. They operate by the concentration of an excessive amount of power at the place where the fault occurs, and in high-power systems much damage may be done before they act. They are also of limited capacity, and either fail or have to be made of a size which is commercially impracticable if they are to deal adequately with the concentrated power of a large transmission and distribution system. There are also the cases, which require quite different treatment, of a line becoming charged to a high potential by atmospheric influences.

Surges. -Then there is the other class of disturbances, which give rise to suddenly developed surges. It has been pointed out in the introduction to this chapter (*see* page 1321) that such violent electrical impulses may be developed in a circuit by improper switching arrangements, as well as by sudden variations of load and by faulty apparatus. A lightning discharge through the line is also an example of an exceedingly rapid electrical impulse which must be guarded against.

The protective apparatus of whatever kind, provided to deal with such impulses, is usually placed mainly in a branch circuit, and has the effect of providing a safe path to earth for the dissipation of the electrical energy suddenly concentrated thereby at a particular point. The selection of the points where dangerous concentrations may occur, and which ought to be protected, is a matter for careful consideration.

All dangerous surgings and lightning discharges develop high potentials, which in the last-named cases may run to millions of volts. Besides a wide range of possible voltages, they also differ in frequency or periodicity from the low frequency of the supply circuits through the much higher frequency of various harmonics (including, it may be, some very high harmonics) to the excessively high frequencies of the lightning discharge referred to elsewhere. For protection against these high voltages and varied frequencies there are available

(*a*) Inductances.
(*b*) Capacities.
(*c*) Spark-gaps of various kinds.

Inductances and Capacities.—The different electrical properties of inductances and capacities, as well as their numerical values, should be borne in mind when dealing with their use as protective devices. Both inductance and capacity introduce *reactance* into the circuit in which they are placed, but whereas the reactance due to inductance is *proportional to the frequency*, that due to capacity is *inversely as the frequency*. Thus (*see* Vol. I., pages 544 and 547):

$$\text{Inductive reactance} = p\,L = 2\pi n L \quad . \quad . \quad . \quad (1)$$

$$\text{Capacity reactance} = \frac{1}{p\,K} = \frac{1}{2\pi n K} \quad . \quad . \quad . \quad . \quad (2)$$

In the annexed Table the values of the reactances for different frequencies are given for approximate values of one of the protective inductances and one of the protective condensers described later. These reactances become the impedances if the ohmic resistance in series is negligible compared with the reactance. The nett result is that for the low frequencies of power circuits the inductance selected has a negligible reactance, but that for the high frequencies of the lightning discharge its impedance due to reactance becomes so high as to limit the value of the current for a voltage of 250,000 volts to 1 ampere. On the other hand, for the low frequencies the impedance due to the capacity is so high as to stop the current entirely when $n = 0$ (the C.C. case), and to cut it down at ordinary frequencies to a small value for even high surge voltages. But for the high frequency of a lightning discharge the impedance of the capacity is so low that the condenser, if placed between line and earth, acts practically as a *dead earth*.

TABLE XX.—VALUES OF REACTANCES IN OHMS AT VARIOUS FREQUENCIES.

Frequency.	Inductive reactance.	Capacity reactance.
0	0	[illegible]
50	0·125	[illegible]
1,000	2·5	[illegible]
1,000,000	2,500	[illegible]
100,000,000	250,000	[illegible]

Spark-gaps.—The third type of apparatus mentioned above (the spark gap) acts quite differently. Electrically, it is a condenser of excessively low capacity, but its action for protective purposes depends upon the relief obtained by the breakdown of the dielectric under the electrostatic stresses when the spark passes and the condenser is discharged. The laws of the electric discharge under ordinary atmospheric pressure have been considered at length in Chapter XVIII. and other parts of Vol. I.

IVa. TYPICAL APPARATUS IN USE

Before describing briefly the arrangements for utilising the devices just referred to, it will be convenient and conducive to clearness to describe some of the apparatus now in use. In doing so, we shall follow the order tabulated on page 1355, describing last of all apparatus which embodies the characteristics of more than one class.

(*a*) **Inductances.**—The inductances used for protective purposes fall into two types according as they are required to offer high impedance (i.) to high-frequency or (ii.) to low-frequency currents.

The first-named type consists of air core or ironless inductances, for, as shown on Table XX., a small fraction of a millihenry is sufficient to give a large reactance in a circuit subjected to the high frequency of lightning discharges. Such inductances are now frequently referred to as "choking" or "choke" coils—terms which are used elsewhere and in other connections in this book, and which well express the effect of the coils in a high-frequency circuit.

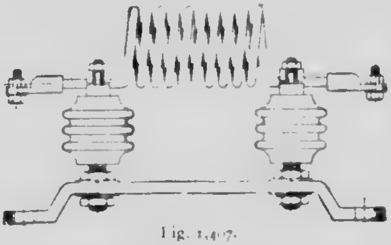


Fig. 1,407.

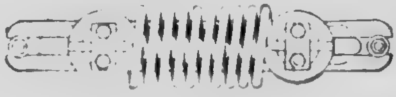


Fig. 1,408.

A High-frequency Choking Coil.

Choking Coils for High Frequencies.—Sufficient inductance to produce the effect required is obtainable in many cases by a few turns of an open spiral such as are shown in elevation and plan in Figs. 1,407 and 1,408, which are from drawings of a standard pattern manufactured by the General Electric Company of London. The spiral is made of stove enamelled copper-wire mounted on porcelain insulators on a cast-iron base for use in circuits in which the low-frequency power currents may have a voltage up to 12,000 volts. There are ten standard sizes with overall lengths varying from 14 to 20 inches and from 8 to 13½ inches high. The gauge of wire used is determined by the maximum load current of the circuit, into which the coils must introduce only an inappreciable resistance. The external diameters of the spirals vary from 2⅜ to 4½ inches, and ten turns are shown. Taking these dimensions, the inductances of the coils will be approximately 0·0024 and 0·0062 millihenry for the unit permeability of the air core.

In practice, much more open coils are frequently used. The coil for which Table XX. is calculated had a diameter of 10 cms., a length of 30 cms., and consisted of twenty turns, its inductance being taken at 0·04 millihenry. The inductance can be increased by using iron, instead of copper, wire. For instance, a coil 12 inches in mean diameter, and consisting of fifteen turns of $\frac{5}{8}$-in. square iron wire, was found to have an inductance of about 0·1 millihenry, whereas for material of unit permeability its inductance would be about 0·057 millihenry. The difference is not so great, however, as might have been expected.

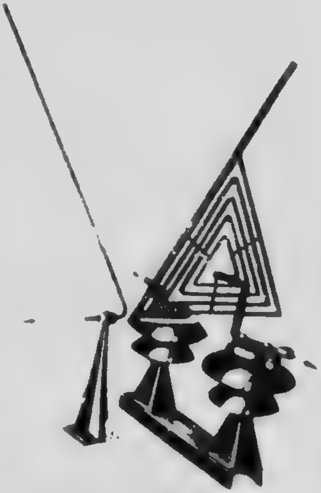


Fig. 1,409.—The Burke Choking Coil and Spark-gap

A curious choking coil, known as "Burke's Arrester," is shown *in situ* in Fig. 1,409; it takes the form of a kind of triangular spiral the line wires being clamped to the bases of the innermost and outermost triangles, whilst one of the outermost long sloping sides is utilised for the insulated side of the horn-gap. The inductance is very low, but sufficient to damp a very high frequency discharge.

A more normal pattern of choking coil for dissipating the energy of high-frequency surges is shown in Fig. 1,410, which illustrates one of the standard patterns of the General Electric Company of Schenectady. The energy such a coil consumes at the ordinary frequency of the line is practically inappreciable.

Choking Coils for Low Frequencies.—These inductances are intended to limit the effect of surges due to short circuits or other sudden disturbances at the frequency (including harmonics) of the power currents. From this point of view, they are sometimes referred to as "current limiting reactances," "current limiters," or more simply "reactors." The last-named term is, however, objectionable.

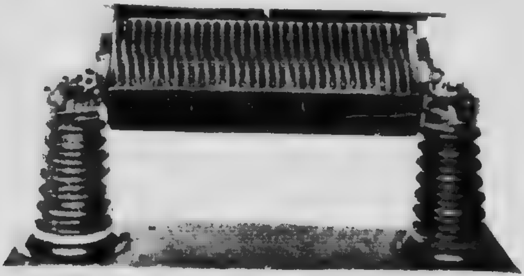


Fig. 1,410.—Another High-frequency Choking Coil.

If unprotected by something more than devices which take an appreciable time to act, a modern large transformer would be subjected to enormous mechanical forces in the event of a dead short-circuit suddenly occurring across two of its secondary terminals. An example of effects which have actually been produced has been given in Figs. 933 and 934. The inductive reactance of such a transformer is less than 3 per cent. or, in other words, the inductive drop in volts due to its reactance is at normal full load less than 3 per cent. If now a dead short-circuit occurs, the instantaneous currents will be $\frac{100}{3}$, or 33 times the full-load currents. But the mechanical forces developed inside the transformer are proportional to the square of the current, and they would thus, for a brief period be $(33)^2$, or 1,090 times the normal forces. It is not therefore surprising that effects such as are depicted in Fig. 933 should be produced. Evidently the effect can be diminished by the insertion of a choking coil in series with the alternator or transformer, provided that the coil be designed specially for the purpose. From the point of view of the designer, two or three conditions emerge from the above and other considerations, but these will be better understood if we first describe some of the inductances in actual use.

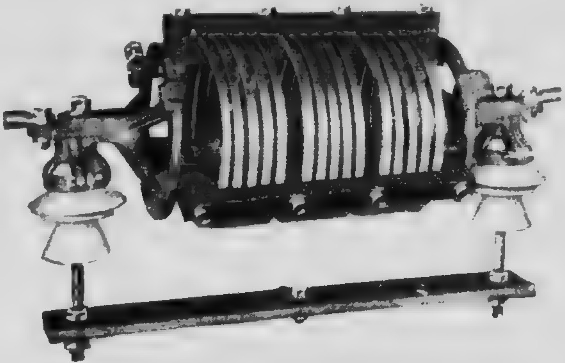


Fig. 1,411.—Choking Coil for 6,600-volt Low-frequency Line.

For comparatively low-voltage lines, up to 6,600 volts, the British Westinghouse Company mount for outdoor service, a 15-turn coil made of square iron-wire, as shown in Fig. 1,411. The reason for using iron instead of copper, notwithstanding its high resistance for steady and low-frequency currents, and also the higher inductance of the coil, is that in high-frequency currents and currents of high density, the "skin effect" referred to elsewhere is so great that its ohmic resistance becomes something like 100 times that of copper, and its capacity for dissipating the destructive energy of a high-frequency surge becomes, therefore, very great. Normally the coil shown will carry a line current of 50 amperes without undue rise of temperature. It is strongly braced with wooden, i.e. non-metallic, clamps to resist the mechanical forces of heavy short-circuit currents, and the mechanical attachments to the insulators are also carefully worked out.

For higher voltage lines, up to 22,000 volts, the same manufacturers mount the coil as shown in Fig. 1,412, so that it can be inserted direct into the overhead transmission line. In this case the coil is made of bare copper wire, and consists of fifteen turns wound upon a mandrel 7½ inches in diameter. The coil shown is designed to carry line load currents up to 100 amperes, the line being secured to the links in the end brackets, and jumper wires being used to make electrical connection to the terminals of the coil. For the above load current the coils are 21 inches long, but similar coils are made with heavier copper conductors up to sizes capable of carrying currents up to 600 amperes, the largest coils being 40 inches long, but practically of the same diameter as the smaller sizes. The clamping cleats are of hard wood, and a substantial hard wood strain post is fixed along the centre line connecting the two end brackets together. These brackets have four spider-arm extensions to carry the clamping cleats and the terminals.

The special feature of the above coils considered as choking coils for low-frequency circuits is the absence of any iron core. Such an iron core would enable the necessary inductance for the low-frequency circuits to be obtained with a lower copper (or C^2R) loss; but if economically designed for normal working the iron would become saturated when the large surge currents pass; its permeability would then be much reduced and the inductance correspondingly diminished just when its effect was most required. On the other hand, if an iron-cored coil were designed to avoid saturation under short-circuit conditions, the whole apparatus would be large and heavy, and the cost would be prohibitive. With no iron core the inductance L remains constant and the reactance voltage, pLC, rises proportionally with the current.

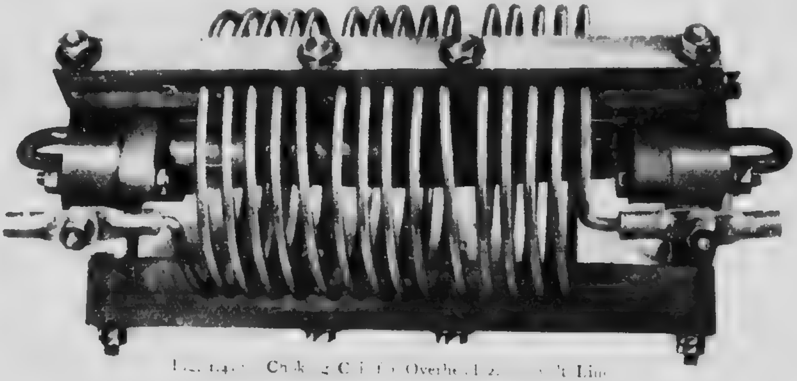


Fig. [illegible].—Choking Coil for Overhead [illegible] Line

Another feature in the design of these coils is the careful limitation of the use of solid metal, except the necessary conductor, and its removal from the neighbourhood of the current. The object is to avoid the formation of eddy currents in the closed circuits of such solid metal, since these eddy currents would act as secondary currents in the apparatus, which would become, in effect, a transformer with short-circuited secondaries, the inductive effect of the secondary currents being, as pointed out elsewhere, to ease the passage of the primary currents by diminishing the total reactance and with it the impedance of the primary coils.

In coils designed for much heavier work and much higher voltag than those described above, this elimination of solid metal is carried mu further, as will be evident from an inspection of Fig. 1,413, whi shows a limiting reactance this type as constructed the General Electric Com pany of Schenectady. Th core is made of concret which is, of course, a non conductor, carefully mix and cast in an iron mould the only metal embedd being the eight small anch plates or sockets at each end, which are to receive th radial brass bolts necessary for holding firm the wooden clamps which keep the windings in their places. The co is hollow, partly because material can be saved and weight reduced without sacrificing the necessary strength or stiffness, but chiefly so that f handling and installation purposes a long iron rod carrying a ring-bolt

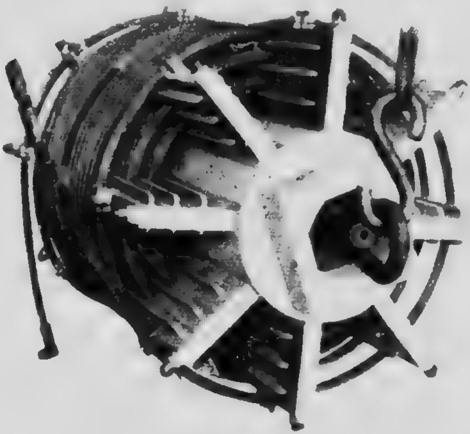


Fig. 1,413. Choking Coil with Concrete Core.

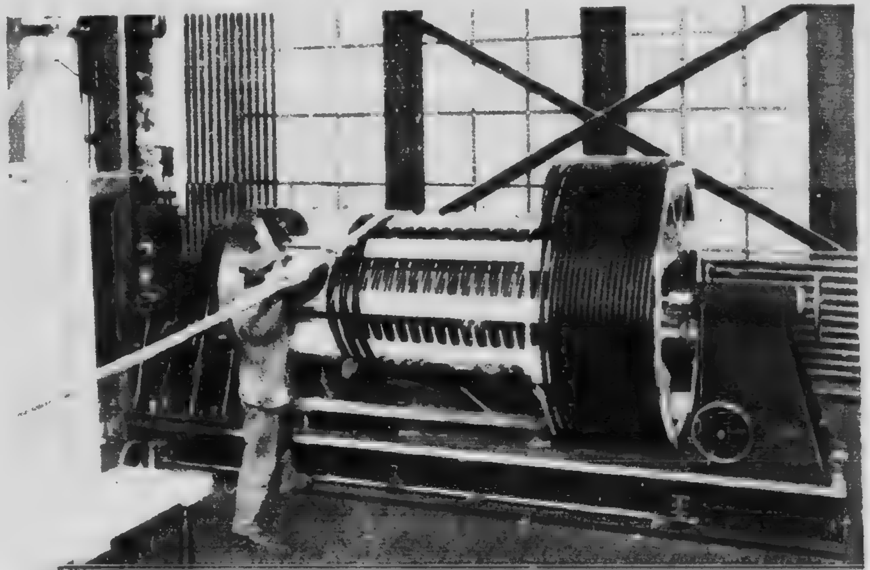


Fig. 1,414. Winding a Concrete-core Coil.

at one end, can be passed through the core from end to end and securely clamped between a screw-threaded nut at the far end and a loose washer and nut at the end nearest the ring. These nuts, plates, bolts, etc., are all removed when the reactance has been installed and before it is used.

The process of winding a large choking coil of this type is shown in Fig. 1,414. The conductor, which consists of bare stranded copper, is wound into grooves in the long wooden clamps, which are made of resin-treated maple and are held in place by the radial brass bolts mentioned above, and which are enclosed in mica tubes. The clamps are also painted with an insulating enamel paint, and are separated from the core by strips of pressboard. Heat shields of asbestos shellaced into the winding grooves keep the wood from contact with the hot copper. The coils are usually wound in two back-turn sections which allows the terminals to be brought out at the ends of the outside layer, thus removing the leads from the core and improving the accessibility. The end turns of the outer layer are given extra spacing for additional insulation, and for reasons explained elsewhere.

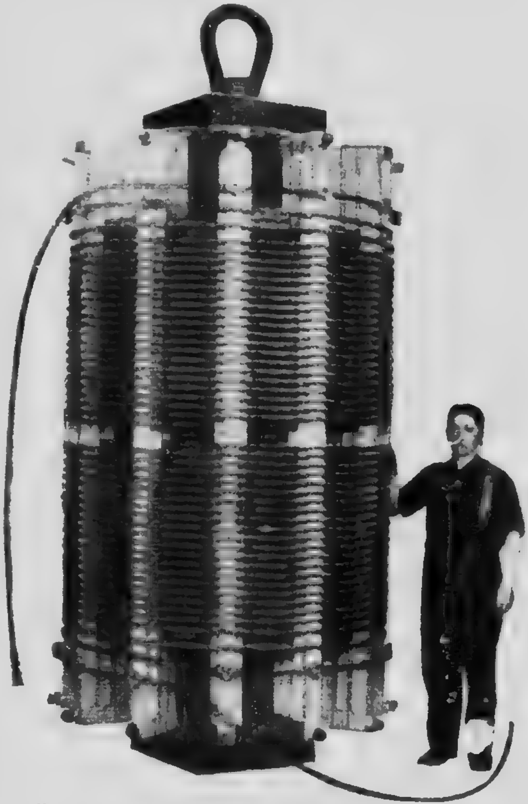


Fig. 1,415.—A 720-*k*V.A. 25-period 600-amp. Choking Coil

A large finished coil so wound is shown in Fig. 1,415, which needs no further description. The "limiting reactance" shown is designed to carry a 600-ampere current on a 25-period circuit and to absorb 720 *k*V.A. The voltage drop between its terminals at full load will therefore be 1,200 volts, and the impedance 2 ohms; the ohmic resistance, R, will only be a small fraction of this impedance, the greater part of which will consist of the reactance, pL, in quadrature with it. This coil was designed to protect the bus-bar sections or groups of generators in one of the largest central stations in the United States, and the total full-load losses in the coil are only 0·12 per cent. of the full-load capacity of the generator protected, or 12 *kw.* for every 10,000 *kw.* of plant. The temperature rise in the copper for full normal load does not exceed 40° C.

In conclusion, Fig. 1,416 illustrates a "limiting reactance" made by the same firm, in which all metal except the conductor is eliminated by first winding the coils in disc shape and then casting twelve radial concrete blocks to hold them in position as shown, the whole standing upon high-voltage insulators. The layers in the concrete are not at right angles to the arms, but sloped alternately in opposite directions, so as to give the maximum distance allowed by the actual dimensions between the turns of successive layers between which the electric P.D. is a maximum.

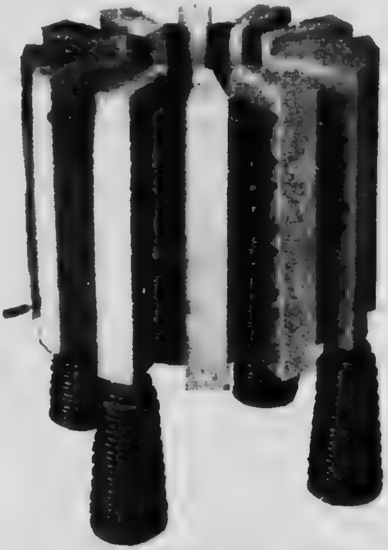


Fig. 1,416.—Choking Coils Imbedded in Concrete.

(*b*) **Condensers.**—The condensers which are to introduce, as protective devices, the electrical properties referred to above into electrical power circuits handling large quantities of power, have to be much more robust in their powers to withstand mechanical stresses due to electrical action than the apparatus used in other applications of condensers. Fortunately the capacity can be quite low, as its value appears in the denominator of the fraction (*see* equation (2), page 1355) expressing the reactance, and a reduction of capacity increases the reactance. On the other hand, the capacity cannot be indefinitely diminished because, if it were, the impedance, even for high frequencies, would remain too high for the relief required when the condenser is in action as a protective device. In the calculations embodied in Table XX the capacity assumed for the condenser is $\frac{1}{100}$th of a microfarad.

The Moscicki Condenser.—One of the most successful condensers for this high-voltage and high-frequency work is the Moscicki condenser, manufactured by Messrs. Isenthal and Co., and the General Electric Company, of London. A section of a single condenser is given in Fig. 1,417. The dielectric is glass of a specially selected kind, having a high breakdown coefficient. The condenser is in the form of a thin glass tube *a a a*, closed at the lower end and constricted to a long neck of thicker glass at the upper ends. The conductor plates of the condenser are formed by coating the inner and outer surfaces of the glass with chemically deposited silver, which is quite free from air bubbles, and is afterwards plated with copper. Connection is made to the inner coating by a metal rod expanded at its lower end into a tight-fitting cylinder and held firmly in its place. The thickened glass at the neck is to enable the dielectric there to withstand the increased electrostatic stress which develops at the edges of opposed charged conductors, according to the electrostatic laws explained elsewhere. As a further precaution, the neck of the tube is inserted in a substantial porcelain insulator corrugated on the outside, and the space between the neck and the porcelain is filled with a solid insulating compound in such a way that the edge of the conductor layer is completely buried in the mass of the compound, so that no surface discharge can take place.

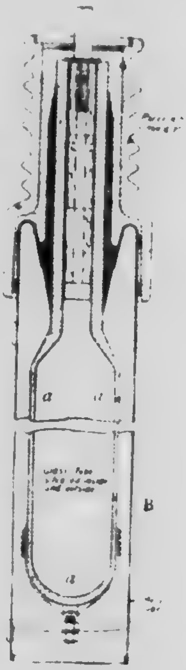


Fig. 1,417.—Section of a Moscicki Condenser

The condenser so formed is mounted in an outer iron tube B, the lower end of the glass tube being supported elastically by means of a rubber sleeve, which is coated with conducting graphite paint. The space between the condenser and the outer tube B is filled with a mixture of glycerine and water, which has a low freezing point and whose function is to distribute by convection any local heating throughout the mass of the liquid.

A single condenser so constructed, having an overall diameter of 8 cms. and overall height of 145 cms., has a capacity rather under 0·005 microfarad, and will withstand a peak pressure of 20,000 volts. A size more convenient for many purposes has an overall diameter of 5 cms. and a height of 61 cms., the capacity being approximately 0·0015 microfarad.

For practical use the condensers are assembled in batteries, as shown in Fig. 1,418, in which there are twelve of the smaller condensers in parallel. The capacity would therefore be about 0·02 microfarad. One advantage of the narrow lateral dimensions is that the paralleling connectors at the top are quite short and practically devoid of inductance.

Spark-gaps.—The earliest effective device employed by telegraph engineers to protect their apparatus from lightning discharges caused by their overhead lines being "struck," was a spark-gap, and the particular forms of such gaps as used in those early days are described in the proper section.

Nature of the Lightning Discharge.—But first it should be explained—and herein lies the key to all the spark-gap safety devices adopted—that the lightning discharge consists of an alternating electric current of high voltage and high frequency. The high frequency, which may be millions of periods per second means, as explained above, that the *impedance* of electro-magnetic apparatus and machinery measured by $\sqrt{R^2 + p^2 L^2}$, is very great, and that if an alternative path to earth across a spark-gap as shown in Fig. 1,419 be provided, the high voltage will more easily break down the dielectric strength of the air than force current through the conducting path of the electro-magnetic apparatus.

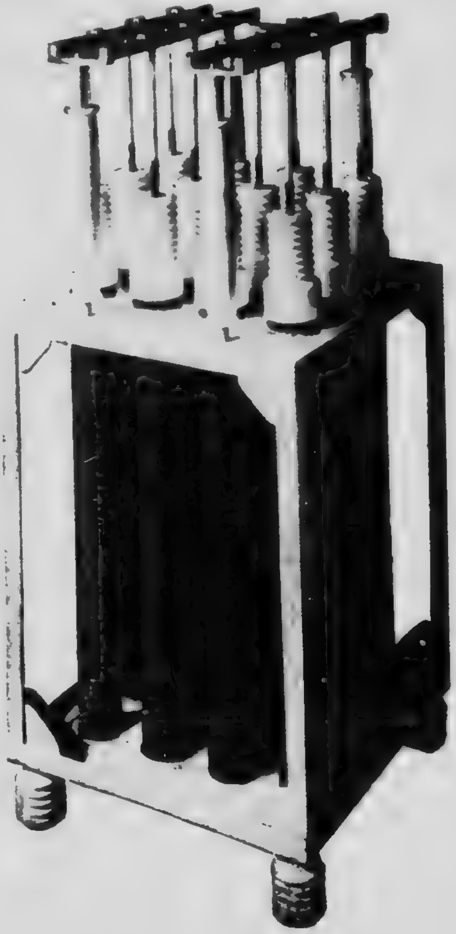


Fig. 1,418. Battery of 12 Moscicki Condensers.

Horn-type Arresters.—This consideration leads to the very wide use of the *horn type* of lightning arrester, the principle of which is indicated in Fig. 1,419. Horns H H, made of galvanised iron or copper $\frac{3}{8}$ inch to $\frac{1}{2}$ inch in diameter, are mounted on suitable insulators according to the voltage of the line to be protected; one of them is joined at L to the line and the other at E to earth. At some part of the line the circuit runs through a machine or piece of apparatus M which is essentially electro-magnetic, and in which either the circuit is directly earthed or at some weak point I the insulation might be broken down by the lightning discharge much more easily than at the air gap G. The electro-magnet M, or the inductance of the circuit between G and the weak point I, offers so great an impedance to the high-frequency lightning current that the insulation breaks down at G, and a spark passes there before the voltage can rise to a dangerous value at I. By the passage of the spark at G the electric stresses are relieved, and as the lightning discharge is of very short duration, extending over only a small fraction of a second, the discharge at G removes the immediate danger.

The above is the theory of all spark-gap lightning dischargers applied to any kind of electric circuit. Where, however, the line at L (Fig. 1,419) is part of a system in which there are high-power generators, the passage of a spark at G may bring serious consequences in its train by the *starting of an electric arc*, which may be continued because of the high voltage on the line and the power of the generators, and which may cause heavy currents to pass at G with serious consequences in all parts of the system. This danger is, as mentioned at page 1354, usually not present in signalling circuits.

The chief safeguard against the danger is the form of the spark-gap adopted. When a horizontal arc is formed in air it is curved upwards (hence the name "arc"), as in Fig. 212, Vol. I. With the electrodes shown in Fig. 1,419 the arc forms first at the narrowest part of the gap, but both by electro-magnetic action and by the movement of the heated and ionised air it is driven upwards, and the spark path becomes longer and longer, until it becomes so long that the voltage available—namely, that of the circuit—cannot maintain the arc and it is ruptured, and the danger referred to above passes away.

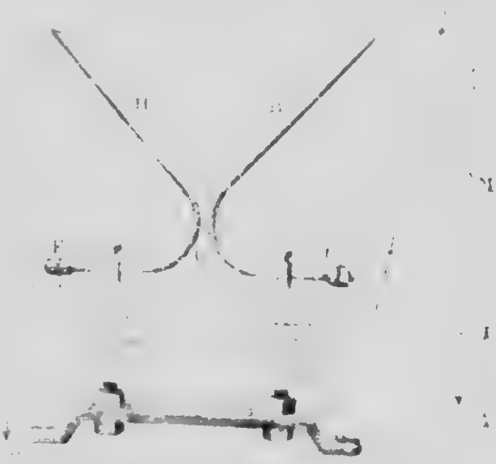


Fig. 1,419.—Horn-type Arrester Showing Connections.

The length of the gap at G must, of course, be sufficient to prevent the ordinary voltage of the line forming an arc there, though as a safety gap it is desirable to make it as short as possible. These conditions are antagonistic. Now the "sparking voltages at different distances" in air have been given at page 130, Vol. I., and some of the factors affecting the discharge have been discussed there and more fully in Chapter XVIII., Vol. I. Reference should be made to these figures and discussions.

In applying the results to the present case, two points must be kept in view. The chief point is that in alternate-current transmission lines it is the "crest" value of the voltage, and not the R.M.S. value, which determines the passage of the spark. Further, it should not be overlooked that at a particular point of such a circuit the voltage may, on account of resonance, rise to a higher value than the generator voltage.

Blow-out Coils.—Even when the arc is eventually ruptured seriou mischief may result if the rupture be delayed too long, and therefore, t assist the travel of the arc along the horns, the device of a " blow-out coil is added to some horn-type arresters. These blow-out coils have bee referred to several times already.* In the case now under consideratio the coil may, as shown in Figs. 1,420 to 1,422, be wound to carry th

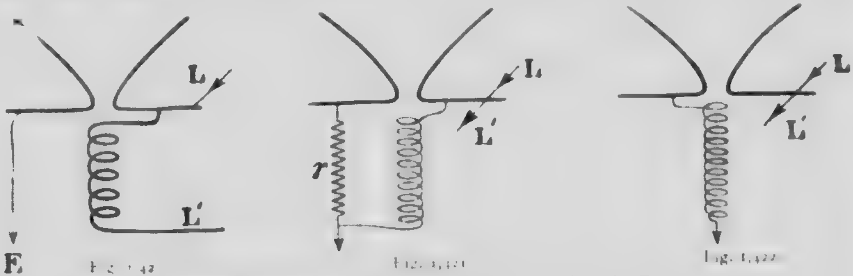


Fig. 1,420 Fig. 1,421 Fig. 1,422

Different Methods of Introducing a Blow-out Coil into the Circuit.

main current (Fig. 1,420), or as a high-resistance shunt to earth (Fi 1,421), or as carrying the spark-gap current (Fig. 1,422). There a obvious advantages and disadvantages in each method, and, also obviously, the working voltage of the circuit must be taken into account. It will be convenient to deal with the low-voltage and the high-voltage apparatu separately.

Low-voltage Circuits.—The design of spark-gaps and their auxilia devices fo the comparatively low voltage bu exposed ci cuits of t trolley wi of tractio systems h been the subject of careful consideration Figs. 1,42 and 1,424 show somewhat diagrammatically in front and side views horn lightning arrester designed by the General Electric Company London for 500-volt c.c. circuits. In series with the main gap there is a second gap B, which is shunted by a fairly low (100 ohms resistance R. A lightning discharge across the gap A, or if heavy enough,

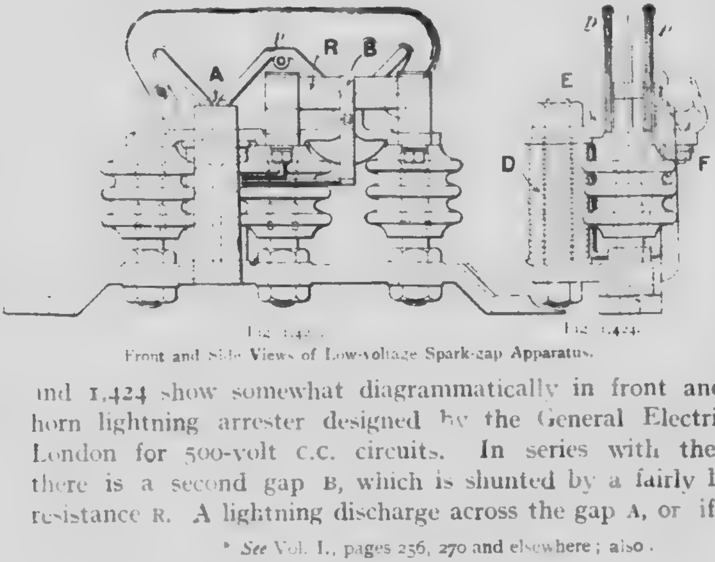


Fig. 1,423. Fig. 1,424.

Front and Side Views of Low-voltage Spark-gap Apparatus.

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* *See* Vol. I., pages 256, 270 and elsewhere ; also .

across both gaps A and B in series, will start an arc maintained by continuous current from the mains across the A gap. Even whilst a lightning discharge across both gaps is taking place, there will be current through the resistance R. The blow-out coil D is connected to tappings from the [illegible] and about half-way across the resistance R, and receives sufficient current to set up the required blow-out magnetic flux, which is concentrated on the gaps by the polar extensions E and F in the plates *p p*. There is thus no inductive resistance in series with the gaps which would introduce impedance into the circuit of the oscillating lightning discharge. The actual apparatus is shown in Fig. 1,425, which is reproduced from a photograph, and should be compared with Figs. 1,423 and 1,424.

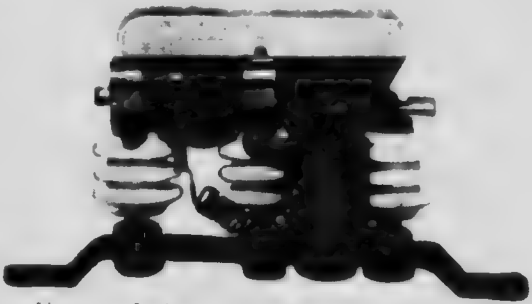


Fig. 1,425.—Spark-gap Apparatus for Low-voltage Circuits.

In the above the device of placing two horn-gaps in series is introduced for the purpose of obtaining excitation for the inductive coil of the blow-out magnet without introducing the impedance of this coil into the discharge circuit. It is, however, sometimes used as shown in Fig. 1,426 to give a graded protection as between heavy and less serious disturbances. The horns are of heavy brass, and one of the gaps B is shunted with a *high* non-inductive resistance, R. A moderate disturbance, such as a static charge on the line due to atmospheric causes, will give rise to a discharge across the first gap A, and the charge will pass to earth through the resistance R. In a more serious disturbance, due to sudden surge or a lightning stroke, the charge on the line will jump both gaps, the second one B offering an easier path than its parallel resistance R. The lower parts of the horns in Fig. 1,426 are fitted with zinc rollers, which can be revolved after a discharge has passed, bringing clean metallic surfaces facing one another ready for the next discharges. The air-gaps are adjustable, and the particular device, designed by the General Electric Company of London, is intended to be used on circuits up to

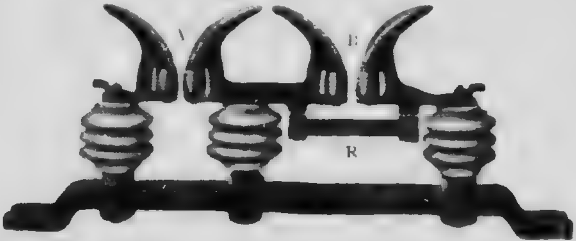


Fig. 1,426.—Double Spark-gaps giving Graded Protection.

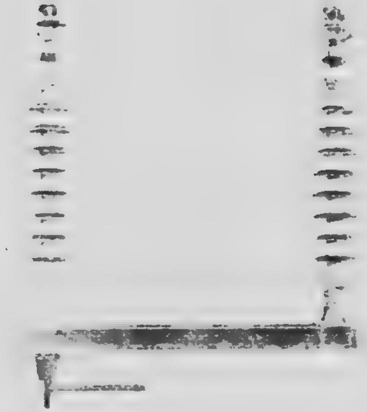


Fig. 1,427.—Sphere-horn Multiple Spark-gaps for 135,000-volt Circuits.

3,000 volts. For higher voltages tw or more sets, placed in series, shoul be used.

Multiple Spark-gaps.—To speed u the action of the spark-gap arrester th General Electric Company of Schenectady places three gaps in parallel a shown in Fig. 1,427, the two lowe being sphere-gaps and the topmost horn-gap. The lower pair of spheres i the main gap taking the heaviest discharges, and the upper pair is a auxiliary gap, to which the horns act a a magnetic blow-out and as an auxiliar gap for low-frequency disturbances.

The properties of the spark discharge have been very fully dealt wit in Vol. I. (*see* pages 645 and 658), and it must not be overlooked that th discharge will pass at a lower voltage if the atmospheric pressure b reduced. In gap dischargers used in mountainous districts at hig altitudes the horns must, therefore, be set farther apart.

High-voltage Circuits.—The high voltages now used on transmissio lines can, however, maintain a much longer arc when it has been started, than can be ruptured by the horn-gap shown in Fig. 1,410. An instance is given in the 20,000-volt arc illustrated in Fig. 213, Vol. I. Additional devices are therefore necessary with the horn-gap arrester if it is to be effective as a safety device. These devices should not interfere with the lightning discharge, but should tend to wipe out the subsequent arc resulting from the line voltage. The most obvious device is to interpose a sufficiently high non-inductive resistance, as shown in Fig. 1,428, between the earthed horn of the gap and the actual earth. Such a resistance will offer practically no obstruction to the very high voltage of the lightning discharge, but will cut down the current, which can be forced through even by the

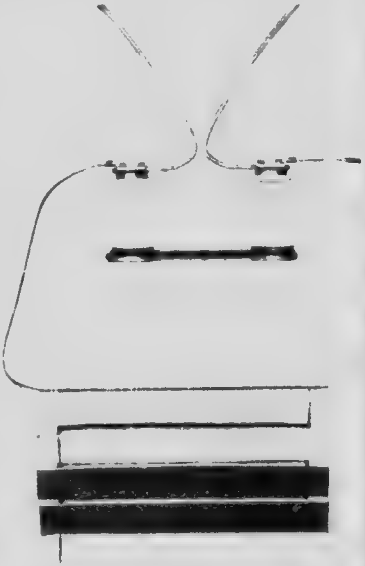


Fig. 1,428.—Horn-type Arrester wit Resistance to Earth.

high voltage of modern circuits. There will thus be a very much lower voltage available for driving an arc across the gap.

The kind and amount of resistance to be used has been the subject of controversy. The kinds used in actual practice are (i.) oil-cooled metal resistances, (ii.) resistances of carbon or carborundum powder, (iii.) liquid resistances, and (iv.) electrolytic-cell resistances. The amount of necessary resistance has been found by experience to be about 1 ohm for every 10 volts of line pressure for overhead lines, and about five to ten times this for cable systems.

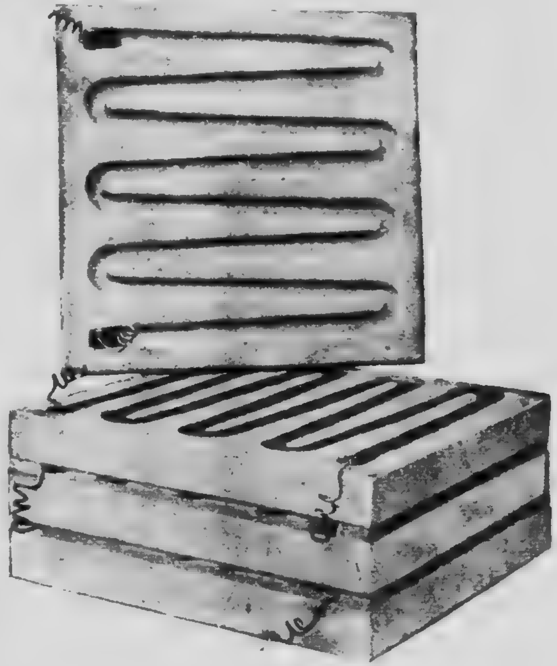


Fig. 1,429.—Special Resistance Slab.

With regard to these kinds of resistance, an oil-cooled metal resistance is expensive, and may become troublesome if the oil gets overheated. The carbon or carborundum-powder resistance is satisfactory and is widely used. A common form of it, known from the name of its inventor as the Brazil resistance, is shown, as manufactured by the Morgan Crucible Company of Battersea, in Fig. 1,429. The resistance material, shown by the zigzag line, is contained in a suitably shaped groove in a horizontal fire-clay slab. The groove is filled with a special carbon powder and covered with a slab of fireproof material. If one slab does not contain sufficient resistance, slabs can be piled on top of one another as indicated and as in Fig. 1,428, which shows a sufficient number of slabs for a 12,000-volt circuit. As the slabs are fireproof and made of insulating materials, no special precautions are necessary. The electrodes are carbon blocks into which connecting rods or wires are fixed.

The third kind of series resistance mentioned above is a *liquid resistance.* Solutions of caustic soda or of carbonate of soda are often used, but such apparatus requires continual attention, in the absence of which it may easily become dangerous instead of being a safeguard. W therefore do not describe them in detail.

The last kind of resistance mentioned, the *electrolytic-cell* resistan is widely used and is very interesting. Its earliest and most usual for is known as the *aluminium lightning arrester*, for it has been used directl as an arrester. For such work, however, it has certain inherent defect and it is now mostly coupled up in series with a spark-gap or gaps, and, a shown elsewhere (*see* page 1235), it is used on circuits of the highest voltag As its action, however, is not that of simple resistance it will be convenient t describe it separately.

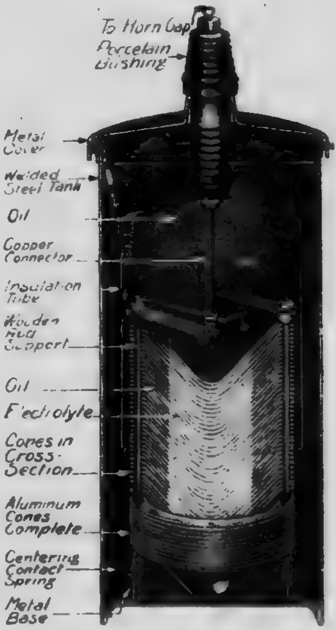


Fig. 1,430.—Aluminium-cell Electrolytic Arrester.

Other Apparatus.—The simple ap paratus summarised on page 1355 ha now been described, but there remain additional apparatus of a more com plicated character, often consisting o combinations of two or more of th simple types with resistance added, and t which we may now refer.

The Electrolytic Resistance or Arres [illegible] which allusion has just been ma [illegible] is one of these, and an exampl the aluminium type, as constructed b the British Thomson-Houston Compa is depicted in Fig. 1,430. The acti depends upon the electrolytic format of a film of aluminium hydroxide on t anode side of aluminium plates, immers in an alkaline electrolyte. The film, thoug very thin, has a very high resistanc but when subjected to a voltage of 3 volts A.C. or 420 (the equivalent voltag C.C., it is punctured with a number of minute holes, and its resistan practically disappears.

The cell in Fig. 1,430, which is designed for use on 25,000-volt A. circuits, is constructed of a number of aluminium cups or cones of the shap shown in section in the upper and in full in the lower part of the figur The cones are inverted and stacked one on another with suitable distanc pieces and with sufficient electrolyte between to fill the central space a shown. They are then immersed in the oil tank, special precautions bein taken to prevent the oil displacing the electrolyte. Connection is mad through an ordinary high insulation bush between the top cone and th line, whilst the bottom cone rests on the outer casing of the tank, whi may or may not be earthed, but is not specially insulated. The oil prevents the evaporation of the electrolyte and improves the insulation. The film of aluminium hydroxide is formed *in situ*.

Originally the cell was connected directly to line as a lightning arrester, it being assumed that the films would always act as insulators, and the device would act as a *multi-gap discharger*. Difficulties, however, arose, due mainly to the slow disintegration and dissolution of the film, as well as to its breaking down at a certain voltage, and therefore, in present practice, a spark-gap, usually of the horn type, is interposed between the line and the cell. To form or to renew the film this spark-gap is bridged, but with a charging resistance interposed to diminish the current, as, with the film broken down, the resistance is very low.

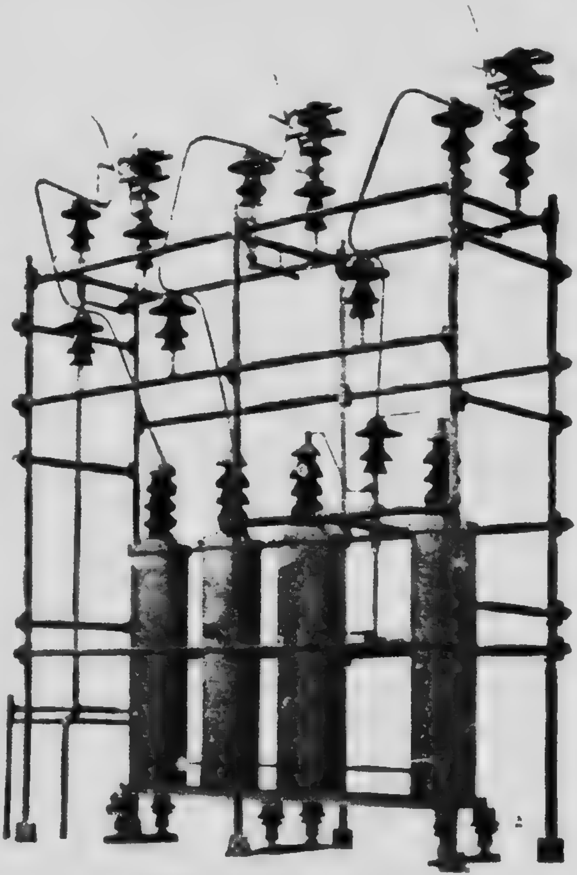


Fig. 1,431.—Aluminium-cell Arresters Protecting a Three-phase H.V. System.

Four of these cells arranged to protect a three-phase 15,000-volt circuit are shown in Fig. 1,431. The cells stand upon an insulated platform, and their outer cases are connected by the horizontal rod seen in the front. Three of the cells are placed, one in each of the line circuits, so that this connecting rod is an insulated star neutral point with the arresters forming the three arms of the star. The fourth cell is interposed between the neutral rod and the earth, and is therefore in series with the three others. The device can obviously only be used when the neutral of the main system (if it be star connected) is insulated. The top connections allow for interchanging the earth cell with one of the line cells, so that the earth ce can be readily connected to line for the reformation of the film of oxi when this becomes necessary.

Such a cell as that described has a large reserve of capacity for exce tional conditions, and a large heat capacity for absorbing the energy of t discharge, but it cannot protect against high-frequency surges unless t high frequency voltage is sufficient to jump the horn-gap.

Aluminium electrolytic arresters of different design can also be us advantageously on low-voltage C.C. *circuits* to protect motors an generators by condenser action against high-frequency lightning discharg and by breaking down of resistance against C.C. surges due to sudd overloads and excess voltages due to various causes. Their use, howeve for these purposes is not, as yet, very extensive, though it may well develo

The Oxide-film Lightning Arrester.—It will be gathered from the abov that one of the drawbacks of the aluminium electrolytic arrester is th necessity for periodical charging if the high-resistance film of aluminiu hydroxide is to maintain its efficiency. The film formed during the char ing process is gradually dissolved by the chemical action of the alkalin electrolyte, and in practice is usually renewed once a day. The process of renewal is not a difficult one, but its daily repetition is irksome from the point of view of maintenance. Attention has therefore been directed to the problem of finding other materials whose chemical and phys properties would render daily charging unnecessary.

The problem has been solved in the research laboratories of the Gener Electric Company of Schenectady, by the use of the oxides of lead whi play so important a part in the lead secondary cell (*see* pages 1053 *et sq.*), the results being published in the *General Electric Review* in September, 1918. Of the oxides of lead the peroxide, PbO_2, is, in the dry state, conductor of electricity, its specific resistance being about 2·5 ohms but depending on the degree of compression.

The specific resistances of the best known oxides of lead are given i Table XXI. in which it will be noticed that in changing from the highest

TABLE XXI.—SPECIFIC RESISTANCES OF LEAD OXIDE.

Oxide of Lead.	Chemical Symbol.	Specific Resistance (cm. measure)
Peroxide	PbO_2	2·5 ohms
Red lead (*minium*)	Pb_3O_4	60 megohms
Sesquioxide...	Pb_2O_3	Still higher
Monoxide (*massicot or litharge*)	PbO	Practically infinite

oxide (PbO_2) to red lead, Pb_3O_4, a change which takes place spontaneously if the oxide be heated to about 150° C., the specific resistance increases about 24 million times. All the oxides are solids, and can, if required, be prepared as powders at ordinary temperatures.

To utilise these properties of the oxides of lead for the purpose in view, the General Electric Company encloses, under slight compression, a layer, about half an inch thick, of the dry peroxide between two electrodes of sheradised iron about 7 inches in diameter, separated by an insulating ring of porcelain. The cells are hermetically sealed by the metal of the electrodes being spun over the porcelain separating rings. When fully formed each cell will hold back a voltage of about 250 to 300 volts, allowing only a small leakage current of a few milliamperes to pass. If, however, an over-voltage be applied, the insulating film of lead oxide is punctured and a discharge current flows freely through the peroxide, but in flowing converts the lead peroxide in its path, especially at the puncture, into the lower and non-conducting oxide, thereby closing the puncture holes and resealing the film.

To construct a lightning arrester the cells to the required number are piled up and clamped together in series as shown in Fig. 1,432, a spark-gap, seen at *a*, being placed in series with them. Of the arresters, which are shown with their covers removed, A is to protect power circuits of 325 to 650 volts, B those of 900 to 1,350 volts, and C is for circuits of 2,100 to 2,600 volts.

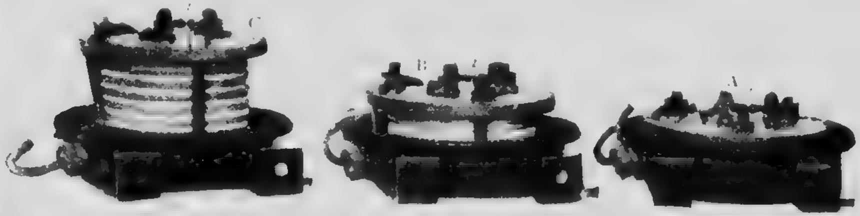


Fig. 1,432.—Oxide-film Lightning Arresters without Covers.

The cell may be "formed"—i.e. its electrodes coated with insulating material—in many ways, but a great number of experiments has shown that the simplest method is to coat the metal electrode with a thin film of varnish by simply dipping the burnished metal into varnish or lacquer before making up the cell. This film of varnish becomes punctured when an over-voltage is applied, and a discharge current flows through the minute holes so produced; this current locally heats the peroxide in the immediate vicinity of the puncture and converts it into red lead or monoxide, thus sealing up the puncture with an insulating plug of the lower oxide. The ohmic resistance of the rest of the cell during such a discharge is only about one ohm, being thus quite low and offering very slight impedance to an A.C. flow of energy at abnormal over-voltages.

Finally, as they are hermetically sealed, the arresters can be installed out of doors as well as indoors with only sufficient protection from th rain to prevent the cells being short-circuited. An outdoor pattern shown in Fig. 1,433, in which the cells are protected from being wetted b the rain by pyramidal petticoats. The side of the housing is remove in the left-hand figure to show the cells arranged in the interior. The arresters with their spark-gaps are designed to protect a 15,000 to 25,00 volt overhead line.

The Giles Valve.—The outstanding defect of the horn-gap discharg is that the particular phase of the current at which rupture occurs is quite a matter of chance. The breaking of a circuit when carrying current should normally take place when the current has been reduced to its smallest value, and therefore in an A.C. circuit when th current has zero value, as otherwise, especially with high voltages and heavy currents, dangerous surges may be set up, as we have seen elsewhere. With a horn-gap the break may take place at the very top of the curve, and this contingency has much limited the use of a devic which otherwise is simple and convenient.

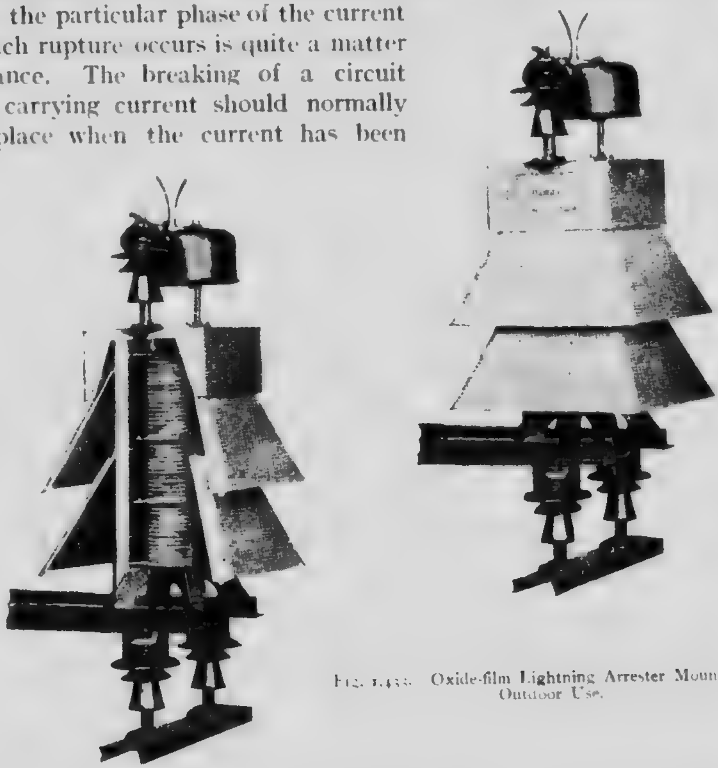


Fig. 1,433. Oxide-film Lightning Arrester Mounted f Outdoor Use.

One of the most successful devices for overcoming the defect, and still using a spark-gap or gaps, is the Giles valve, an external view of which is given in Fig. 1,434, and a section through one of its elements in Fig. 1,435. The electrical connections are shown diagrammatically in Fig. 1,436, which is taken from a paper by Mr. Giles. Dealing first with the diagram, the line L L is connected to a spark-gap e^1 e^2, the farther electrode e^2 of which is connected, through a resistance R, to the first electrode of a series of spark-gaps e^3 e^4, e^4 e^5, e^5 e^6, and e^6 e^7. All these electrodes are insulated except the last e^7, which is connected to the earth plate E. Each insulated electrode from e^3 onwards is so shaped as to form one plate of a small condenser, of which E is the other plate

In practice the first spark-gap has hemispherical electrodes e^1 e^2 (Fig. 1,435), enclosed in a glass tube to protect it from dust, and its length can be adjusted by moving the upper electrode e^1. The resistance R is a wire resistance of about 1,600 ohms, mounted on a vertical insulating tube. The discs e^3, e^4, etc., are made of non-arcing metal, and form both the electrodes of the multiple spark-gaps and the insulated plates of the condensers, of which the central rod E is the earth plate; they are insulated from one another and from E by the micanite sleeve t^1 and the micanite flange rings *r*, which form the solid dielectric of the condensers. The last disc E^{17} is directly connected to E. The resistance R has a value, as mentioned, of about 1,600 ohms, but the effective resistance is reduced, by placing from 6 to 12 columns in parallel, to a value which practice and theory have shown to be more suitable. The parallel columns are electrically connected by the ring A (Fig. 1,434), which is joined to line by the rod B supported and insulated by the central column.

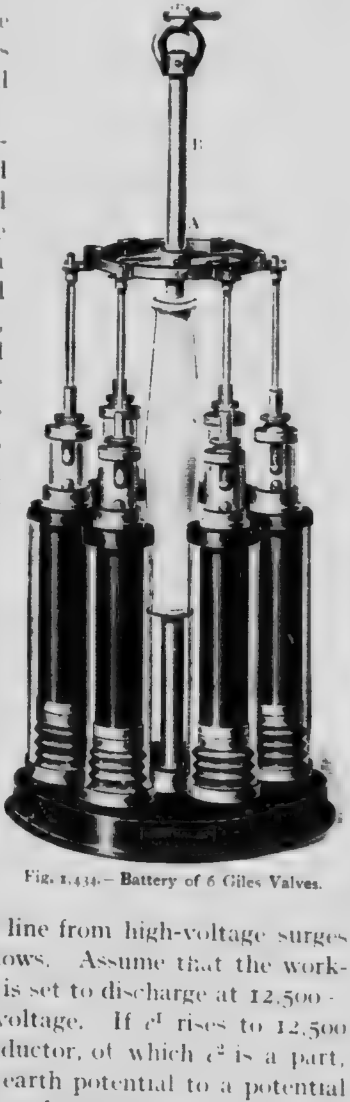


Fig. 1,434.—Battery of 6 Giles Valves.

The apparatus is designed to protect the line from high-voltage surges of low frequency, and acts somewhat as follows. Assume that the working voltage is 10,000, the first spark-gap e^1 e^2 is set to discharge at 12,500—that is, at 25 per cent. above the normal voltage. If e^1 rises to 12,500 volts, a spark will pass across, and the conductor, of which e^2 is a part, will be charged and its voltage raised from earth potential to a potential sufficient to drive a spark across the next much smaller gap between e^3

and e^4. The action passes along the line of gaps, and finally the potential of e^{16} is raised sufficiently for a spark to pass to the earth plate e^{17}. In series with all these condensers there is the resistance R which plays its part with the fifteen spark-gaps in dissipating the energy of the discharge, but in addition limits the current passing, and therefore the total energy dissipated. On this account more than one column of valves is necessary, it being considered that the best value for the final ohmic resistance is in the neighbourhood of 70 ohms. To reach this value about 22 columns would be necessary, assuming discharges to be taking place simultaneously in each.

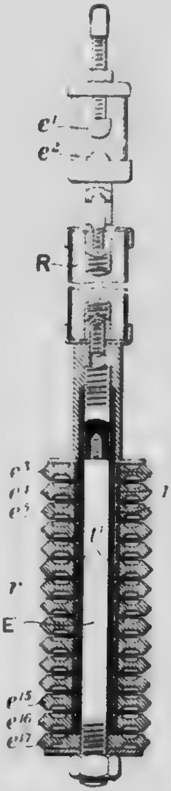


Fig. 1,435.—Section of a Giles Valve.

Static Charges.—Allusions have been made above to the necessity for protection against charges which accumulate especially on overhead transmission and distribution lines, and are due to atmospheric causes. In ordinary weather, and without reference to the disturbances caused by storms, the electric potential in the atmosphere differs in different localities and at different altitudes, and changes somewhat slowly from time to time. By actual contact charged clouds, snow or hail may communicate electrical charges to the line, which may also be under electric induction. Thus the electric potentials of the atmosphere surrounding an overhead line in different parts of its route may differ by thousands of volts. The line being a conductor must take up a kind of average value as regards these potentials, and will become statically charged wherever this average value differs from the potential of the atmosphere in the immediate vicinity. The voltages involved are so great that they may lead to serious breakdowns of the insulation of the machines or the mains, if nothing be done to dissipate them before they assume dangerous values.

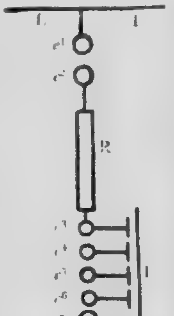


Fig. 1,436.—Diagram of the Giles Valve

A simple though somewhat costly method of protection external to the circuit against the dangers of static charging of an overhead line is to run a wire, earthed at frequent intervals, above and parallel to the transmission lines, the wire being supported on the same poles.

The simplest method of protection is to provide permanent leaks to earth, so designed as not to interfere with, or cause serious dissipation of, the electric energy handled by the power system. For star-connected

A.C. systems with an earthed neutral, such a leak is provided by the system itself, though on long lines additional devices may be necessary. For a delta-connected A.C. system, everywhere insulated, leakage coils of high inductance would be effective by connecting each phase to earth

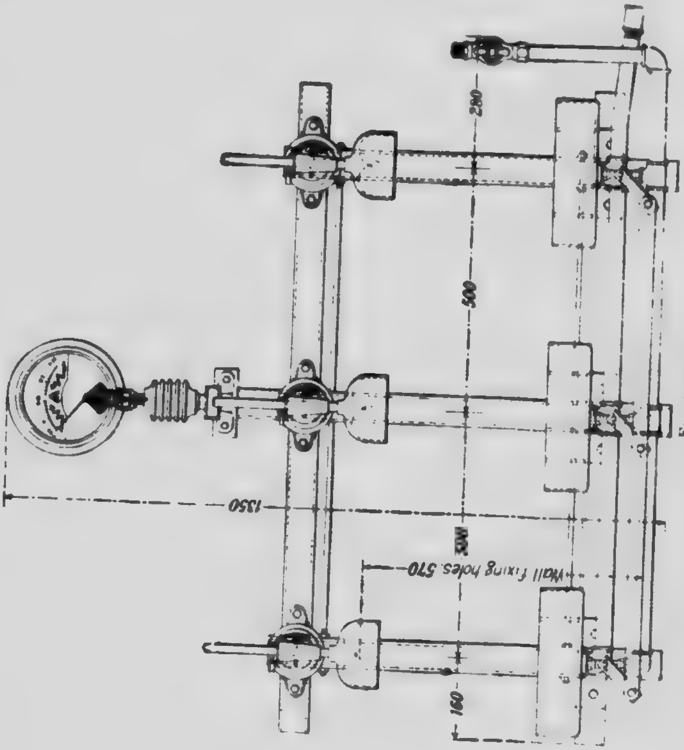


Fig. 143[illegible]. Details of the Fitting for a Water-jet Resistance.

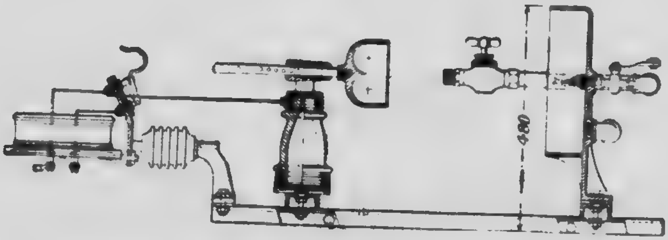


Fig. 14[illegible]

at carefully selected points. Such leaks will allow the static charges to be dissipated without appreciable loss of energy from the power system.

Water-jet resistances.—Metallic resistances of sufficiently high inductance and ohmic resistances are somewhat expensive. Comparatively inexpensive water resistances, the fittings for which are constructed as shown in Figs. 1,437 and 1,438, are therefore used. Fig. 1,437 gives a side view, and Fig. 1,438 a front elevation; the drawings are partly in section and partly in outline, and it is possible to make out all the important details. The resistance consists of a jet of water rising from an earthed nozzle *n* (Fig. 1,437), and striking against an inverted cup, which is connected to the line to be protected. This jet, adjustable in length and cross-section, has, with ordinary water, a sufficiently high resistance, which may be anything from 10,000 to hundreds of thousands of ohms. The apparatus, the principal dimensions of which in millimetres are given in the figures, is designed for an 18,000-volt three-phase system, and the jets have a resistance of about 15,000 ohms per phase. Methods of insulation and connection can be made out, and it will be noticed that an ammeter is inserted in one phase to measure the current to earth. The water having struck the inverted cup, falls back into the basin, and can either be allowed to run to waste or be pumped back into the jet pipe. A similar piece of apparatus, as made by Messrs. Isenthal and Co., and the General Electric Company of London, is shown in Fig. 1,439, which is reproduced from a photograph.

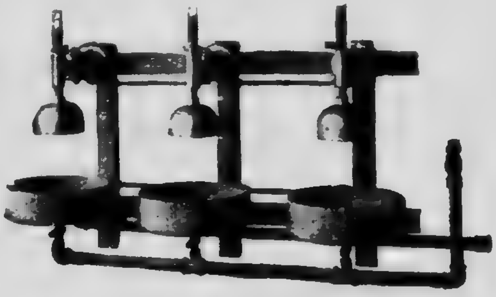


Fig. 1,439.—Water-Jet Resistances.

Water-jets are not recommended for voltages above 40,000 to 50,000 volts, unless they are of very perfect design and are carefully and frequently examined. The necessary water should be readily and cheaply obtainable.

IVb.—PROTECTION OF TYPICAL CIRCUITS

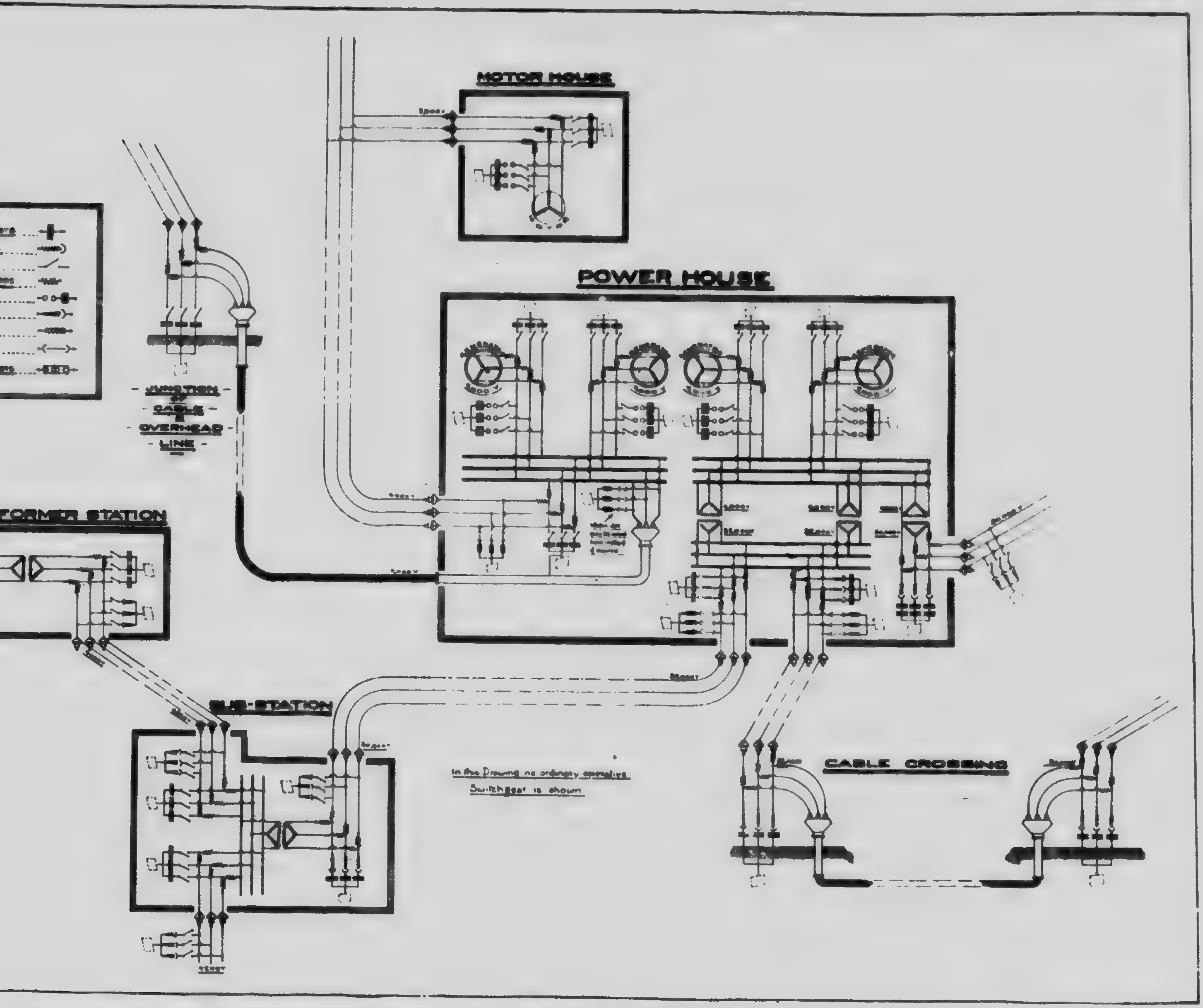
This section would not be complete without some reference, however brief, to the distribution of the protective devices which have been described, and some indication of the salient points at which it is considered necessary to install them.

Condensers and Valves.—In view of the admitted defects of the horn-gap arrester and other spark-gap devices, to which reference has been made elsewhere, it has been pointed out that transmission and distribution systems can be efficiently protected from lightning discharges as well as surges without the use of exposed spark-gaps.

Messrs. Isenthal and Co., the manufacturers of the Moscicki condensers and the Giles valves, contend that these devices, combined with some of the simpler devices previously described, will efficiently protect the system

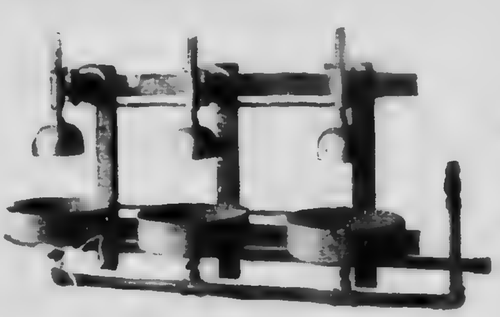
PLATE XVI.

PROTEC


MOTOR HOUSE
POWER HOUSE
JUNCTION OF CABLE & OVERHEAD LINE
FORMER STATION
SUB-STATION
CABLE CROSSING
In this Drawing no ordinary operative Switchgear is shown

PROTECTION OF TYPICAL CIRCUITS FROM ATMOSPHERIC AND OTHER ELECTRICAL DISTURBANCES WITHOUT USING EXPOSED SPARK-GAPS.

[illegible] water resistances the fittings for which are constructed as shown in Figs. 1,437 and 1,438 are there used. Fig. 1,437 gives a side view, and Fig. 1,438 a front elevation; the drawings are partly in section and partly in outline, and it is possible to make out all the important details. The resistance consists of a jet of water rising from an earthed nozzle *n* (Fig. 1,437), and striking against an inverted cup, which is connected to the line to be protected. This jet, adjustable in length and cross-section has, with ordinary water, a sufficiently high resistance, which [illegible] anything from 10,000 to hundreds of thousands of ohms. The apparatus [illegible] principal dimensions of which in millimetres are given in the figures [illegible] designed for a [illegible] 18,000 [illegible] phase system, and the jets have a resistance of about 15[illegible] phase. Methods of insulation and [illegible] can be made out [illegible] will [illegible] noticed that an ammeter is [illegible] in one phase to [illegible] earth. The water [illegible] the inverted cup [illegible] back into [illegible] either [illegible] waste or be [illegible] the jet [illegible] of apparatus [illegible] Messrs. Isenthal and Co. [illegible] the General [illegible] Co. [illegible] London is shown in [illegible] which [illegible] a photog[illegible]



[illegible] W[illegible] S[illegible]

Water-jets are not recommended for voltages above 40,000 to 50,000 volts, unless they are of perfect design and are carefully and frequently examined [illegible] water should be readily and cheaply [illegible]

[illegible] PROTECTI[illegible] [illegible]

This section would not be [illegible] ever brief, to the distribut[illegible] described, and some indication [illegible] sidered necessary to install the [illegible]

Condensers and Valves. [illegible] horn gap arrester and other spark gap [illegible] been made elsewhere it has been [illegible] tribution systems can be efficient[illegible] well as [illegible] the [illegible] has [illegible] dis[illegible] damages [illegible]

Messrs. Isenthal and Co., the [illegible] and the Giles valves, contend that [illegible] simpler devices previously described [illegible] Moscicki condensers [illegible] combined with some [illegible] protect the system

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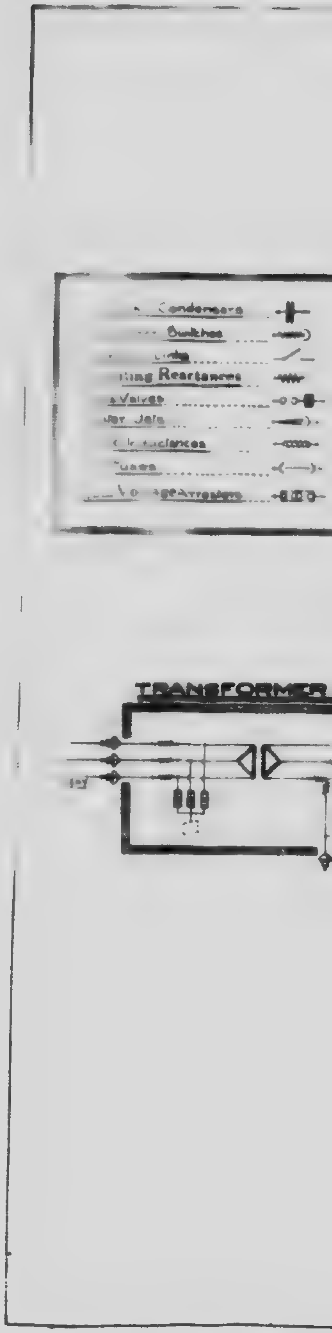
PLATE XVI.



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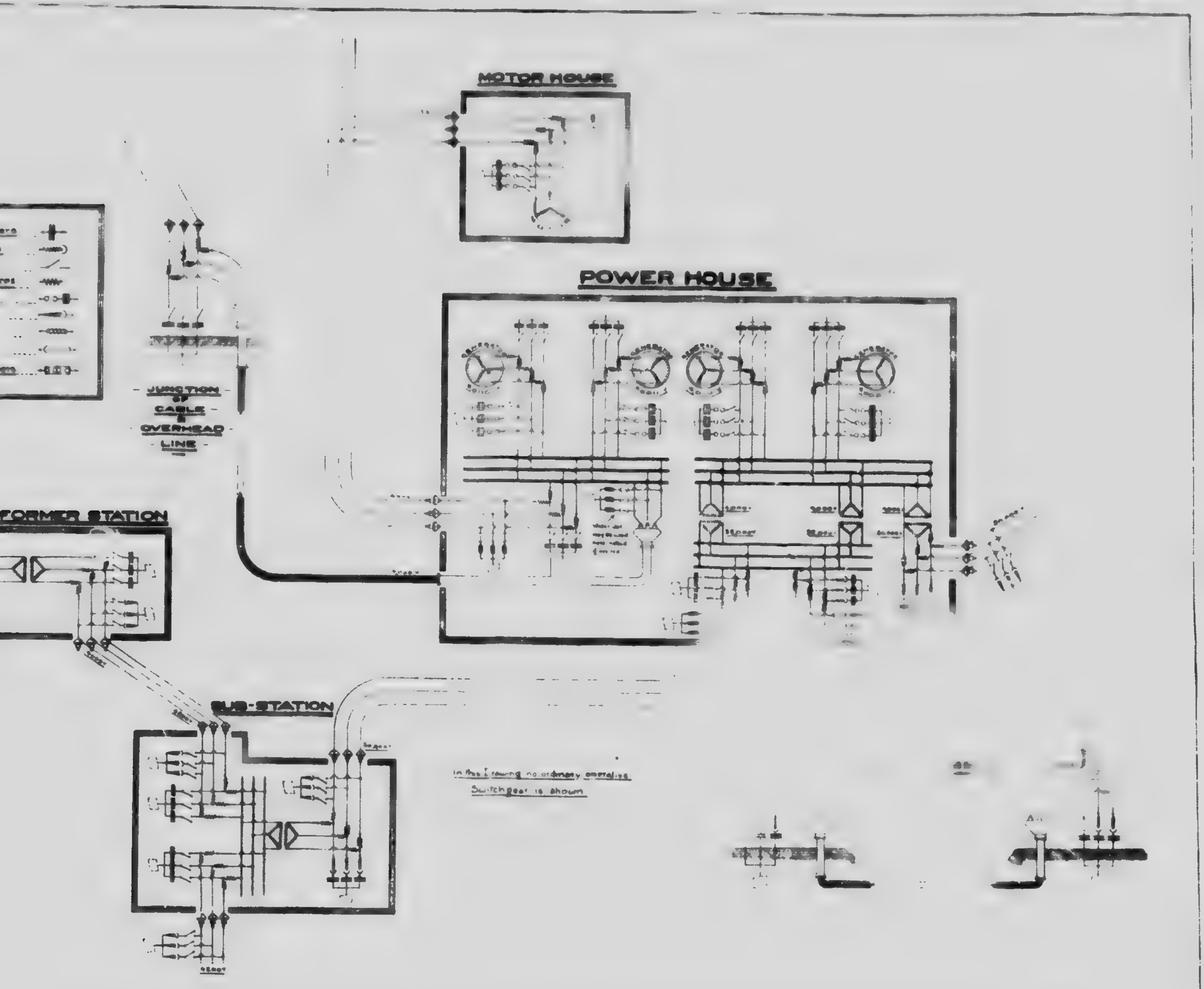
MOTOR HOUSE
POWER HOUSE
JUNCTION OF CABLE & OVERHEAD LINE
FORMER STATION
SUB-STATION
In this drawing no ordinary operating Switchgear is shown

Protection of Typical Circuits from Atmospheric and other Electrical Disturbances without Using Exposed Spark-gaps

by apparatus connected permanently to the lines in such a way as to run little or no risk of the connection being impaired after the devices have operated.

In Plate XVI., for which the author is indebted to Messrs. Isenthal, the typical parts of most systems are taken one by one, and it is shown diagrammatically where the protective devices are to be placed and what devices are to be used at different points to ensure protection against all impulsive disturbances and against static charges due to atmospheric electric action. The diagram is strictly confined to indicating these positions, and ordinary switching and other apparatus are not included.

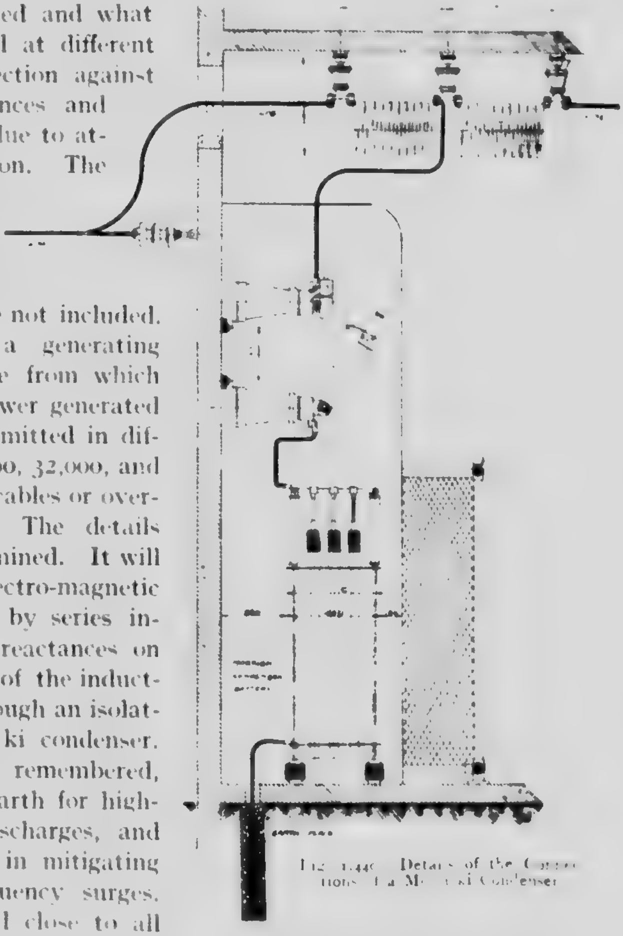

Fig. 1440.—Details of the Connections of a Moscicki Condenser

The plate shows a generating station or power house from which the three-phase A.C. power generated at 4,000 volts is transmitted in different directions at 4,000, 32,000, and 50,000 volts, either by cables or overhead lines, or both. The details should be carefully examined. It will be found that all electro-magnetic apparatus is protected by series inductances or limiting reactances on each phase, the middle of the inductance being earthed through an isolating link and a Moscicki condenser. The latter, it will be remembered, forms almost a dead earth for high-frequency lightning discharges, and assists the inductance in mitigating the effect of low-frequency surges. Giles valves are added close to all generators or motors to deal still more effectively with these low-frequency surges.

All overhead lines are provided with series inductances and earthed condensers in shunt in each phase at each end interposed between the lines and the apparatus to which they are connected, whether busbars, generators, motors, or transformers. In addition, static discharges are guarded against by direct leaks to earth at each end of each overhead line conductor, the leak being deprived of tendency to absorb appreciable energy from the line currents by the interposition of either (i.) a high inductance iron-cored choking coil, or (ii.) a water-jet resistance.

Wherever a cable is joined to an overhead line the junction is also protected by series inductances and earthed by condensers placed on a shunt path, though opinion is divided as to whether this is worth doing for the short length of cable at a road crossing. At the "transformer station" the exit lines, being only at 250 volts, are deemed to be sufficiently protected by a series inductance and multiple-spark gaps in a shunt circuit. Limiting reactances, such as described at pages 1358 to 1362, are not shown in the diagram. When these are used to protect generators they should be placed between the generator and the Giles valve or Moscicki condenser.

Details of the installation of an inductance in series with a Moscicki condenser in leak are given in Fig. 1,440 for an incoming, 18,000-volt, overhead line. The principal dimensions are given, and the apparatus has all been sufficiently described elsewhere, with the exception of the isolating switch A, which has an interesting device for securing a carbon break making a good metallic contact when the switch is closed. A carbon cylinder, with a rounded end a_1 fits loosely in the fixed copper cylinders s s, whilst the movable contact tongue c of the switch has a carbon tip a_2. This contact tongue is so shaped and mounted that when the switch is being closed the two carbons just make contact, but as the arm is driven home the loose carbon a_1 is driven up within the lower cylinder s, and the metal of c makes good rubbing contact with the horizontal lower face of s. On opening the switch, the metal surfaces first break contact, but the circuit is still held closed by a_1 dropping down, and the final break and spark occur between the surfaces of the two carbons a_1 and a_2. These carbons can be readily and cheaply renewed when it is necessary.

The foregoing pages of this chapter, whilst by no means exhaustive, will, it is hoped, give the reader some idea of the extent and fascinating scientific nature of the subject of the protection of electric power circuits, a subject upon which the last word has not yet been said.

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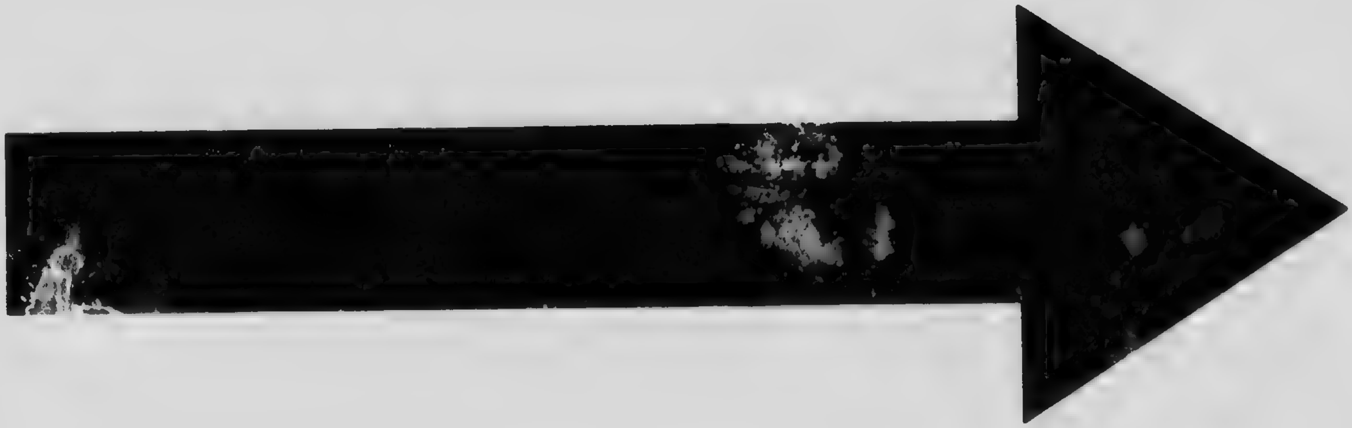

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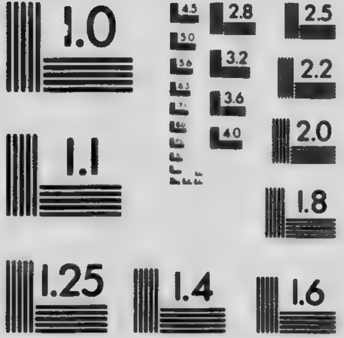

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